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UNIVERSITY OF ALBERTA

MEASURING THE CHARACTERISTICS OF SOIL EROSION ON AGRICULTURAL LANDSCAPES IN EAST - CENTRAL ALBERTA

by

ROBERT W. HOWITT

A thesis submitted to the Faculty of Graduate Studies and Research in partial fullfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY.

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

SPRING, 1991

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THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

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MEASURING THE CHARACTERISTICS OF SOIL EROSION ON AGRICULTURAL LANDSCAPES IN EAST - CENTRAL ALBERTA

Submitted by:

ROBERT W. HOWITT

in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY IN SOIL SCIENCE.

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ABSTRACT

Water erosion is a continuing problem on agricultural landscapes and to date only limited progress has been made measuring and modeling erosion in relation to complex surface form. An open landscape approach was used to measure water erosion on agricultural landscapes in east-central Alberta using a combination of techniques (^{137}Cs, erosion pans, rill meter, and soil properties) from 1985 to 1989. Seven sites were selected to study water erosion; one of which was selected for detailed study using a digital terrain model to link erosion measurements to surface form. Soil losses and soil gains were evaluated in relation to land surface form using statistical and digital terrain modeling techniques.

Water erosion was found to be highly variable in space and time. Rill erosion caused most of the soil loss but was confined to very small portions of the landscape. Most of the soil eroded by rill processes was deposited in the basin and not lost to the surface water system. Most of the soil redistribution occurred over several hours in the case of a summer rainstorm or over several days in the case of springmelt events. Locations of measured rill and interrill erosion or deposition exhibited characteristic forms that could be used to identify them. Erosional or depositional soil profiles could also be identified using digital terrain derivatives. A conceptual model of water erosion was proposed based on existing literature and measurements of water erosion. It consisted of five independent components (climatic probabilities, cropping and management, soil redistribution, digital terrain and soil properties) and takes into account the measured spatial and temporal variability of water erosion at one site in east-central Alberta.

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CHAPTER 1

MEASURING AND MODELING SOIL EROSION ON AGRICULTURAL LANDSCAPES

THE PROBLEM

Soil erosion is a process occurring on a variety of scales in time and space. Geologic erosion is that form of the process which results in the wearing down of rocks, the formation of sediments and which occurs over the longest time scale and largest space scale. Erosion on cultivated agricultural landscapes occurs on a shorter time scale and a smaller space scale compared to geologic erosion. Erosion on agricultural fields occurs on a time scale of decades and a space scale of meters to several hundreds of meters. Within the time frame of one or two human generations, the effect of soil erosion due to agricultural use of soil can result in reduced productivity and possible increased sediment loads in rivers and streams. Erosion on agricultural fields has a negative impact on man's ability to produce food and fiber.

Reduced productivity is related to the loss of nutrients for plant growth and reduced soil quality for seed germination and plant growth. Negative environmental impacts are related to the possible addition of nutrients and sediments into rivers and streams resulting in increased aquatic organisms growth and siltation of the stream bed. In order to determine the relative or absolute impacts on crop production and the environment, reliable estimates of the severity and extent of erosion in relation to the dominant controlling factors are required.

Rill and interrill erosion are two related processes involved in the redistribution of soil and geologic materials on the landscape by water. Interrill erosion involves the movement of soil over short distances (cm to m) as a result of detachment and transport by surface water. Rill erosion is caused by the concentrated flow of water over the landscape

and results in long narrow channels in the soil that can be filled and smoothed by cultivation. Rill erosion occurs on a larger scale compared to interrill erosion and results in soil detachment and transport over considerable distances (m to km).

Springmelt erosion occurs as a result of snowmelt and runoff over frozen ground and is most pronounced on summerfallow fields due to the rapid melting process and a lack of plant roots to stabilize the topsoil. Springmelt occurs on an annual basis and may be the single most important cause of soil erosion by water in east-central Alberta even if the amounts eroded are less than existing tolerable soil loss guidelines as discussed by Chanasyk and Woytowich (1987). Summer rainfall in that region can also cause significant soil erosion and deposition, albeit infrequently.

Soil erosion on agricultural fields in east-central Alberta is a continuing and persistent problem as observed during soil survey activities (Wyatt et al. 1944; Macyk et al. 1985; Howitt 1988). Observations of erosion during a soil survey are generally qualitative and thus do not quantify soil loss or gain that has occurred. However, they bear out the occurrence of water erosion and highlight the temporal and spatial variability of soil redistribution.

Summerfallow fields (cultivated) represent a worst case situation with respect to soil erosion, and since summerfallow is still a commonly used agricultural management practice in east-central Alberta, this research will focus primarily on measuring and modeling soil erosion on summerfallow fields under existing crop rotations.

The purpose of this research is to quantify soil erosion and deposition on agricultural landscapes as a function of surface form, soil properties and microtopography resulting from erosive meteorological events. This project will focus on soil erosion in summerfallow fields during springmelt and summer rainfall. The spatial and temporal aspects of soil erosion are not generally addressed explicitly by erosion models and yet have been observed to be important for estimating runoff and erosion in other parts of Alberta such as the Peace River Region (Chanasyk and Woytowich 1986; 1987).

APPROACHES TO MEASURING WATER EROSION

Many approaches have been taken to measure water erosion in the field and in the laboratory. The method of measurement used is dictated by the objectives of the research and the approach taken by the researcher. Measurements of the sediment load at the outlet of a basin indicate total soil loss from the basin but do not indicate sediment sources. Laboratory measurements of erosion give the relative susceptibility of different soils to raindrop impact under controlled conditions but do not necessarily reflect field conditions. Field studies to measure soil erosion are often limited by the difficulty of controlling all variables or variability in soil properties and are often subject to the sporadic nature of erosive meteorological events. Field studies provide a means to identify sediment source locations and sinks for deposition. They also provide an indication of the nature and scale of the processes operating on the landscape in a three dimensional perspective.

Five methods for measuring water erosion in cultivated agricultural fields will be discussed: plot studies, erosion pan studies, rill meter studies, the use of ^{137}Cs and landscape analysis.

Plot Studies

Rectangular plots were used for data acquisition in the development of the Universal Soil Loss Equation (USLE) (Wishmeier and Smith 1965) and were used to develop slope length, slope gradient, soil erodibility, cropping and erosion control factors for the USLE. Plots still form the basis for calibrating the USLE under different climatic and soil conditions, but many variations occur in plot dimensions and collection equipment (Hayward 1967). Plots are usually of fixed and bounded area on a uniform slope. Soil erosion and runoff are measured at the outlet of the plot either by collection or by timed-interval sampling of the effluent. Outflow of water and sediment represents soil loss or soil yield (Chanasyk and Woytowich 1987).

Plot studies are well suited to measuring runoff and soil erosion on an area basis because plot boundaries serve to define the area of sediment and water production. Adjacent plots with different treatments in terms of crop type, soil management practice or erosion control practice can be compared quantitatively in terms of response to rainfall or snowmelt events. Plot boundaries and the cultivation pattern on the plot explicitly control the influence of downslope erosional processes. Control over slope length, gradient and area of production is important for the comparison of results from one plot to another but limits extrapolation of results to larger land areas where the pattern of cultivation and the slope gradient are not congruent. Plot studies measure the relative contribution of single slope segments to erosion but do not measure total runoff and sediment redistribution (soil loss and soil gain) within a watershed or field. Thus, 'scaling up' (Roels 1985) from plots to watersheds and/or to landscapes is complicated. Plot results are also limited in their applicability to larger and ultimately more complex landscapes where slopes are infinitely variable due to the shape of the landscape. Roels (1985) discussed many of the difficulties in estimating soil loss at a regional scale based on plot studies. These difficulties include poor sampling design and inadequate analysis of data. He noted also that no standards exist for plot dimensions and that when different data sets with different measuring units are compared, unit conversions (from open to closed plots) are necessary and can lead to biased data. Roels concluded that total soil loss on land units was best determined by "measurement of rill erosion and sampling the interrill and pre-rill subpopulations".

Plot studies are also limited by the imposition of artificial boundaries on the landscape because these boundaries can interfere with the surface and subsurface flow of water. Runoff and soil yield from plots via processes of rill and interrill erosion are lumped; thus, there is no mechanism for identifying the relative contribution of each process. Comparison of plot data between studies may be difficult or impossible given the difficulties associated with variable plot length and width as noted by Hayward (1967) and there may also be edge effects. Finally, plots are expensive to install and many years of

data are required (15 or more years according to Roels 1985) for definitive conclusions to be drawn.

^{137}Cs Studies

The radioactive fallout product ^{137}Cs found in soils in minute quantities provides a tracer of soil redistribution over the past 30 years (de Jong et al. 1983). ^{137}Cs is strongly adsorbed onto the fine colloidal particles in the soil and is believed not subject to relocation by leaching or other soil processes. Relocation of ^{137}Cs is thought to result solely from erosion of solid soil materials. The proportional loss of ^{137}Cs (Bq/m^2) at a study site is calculated by the following relationship (de Jong et al. 1983):

$$^{137}Cs \text{ loss} = [0.95\ ^{137}Cs_c - {}^{137}Cs_e] / [0.95\ ^{137}Cs_c]$$

where: $^{137}Cs_c$ (Bq/m^2) is the concentration of ^{137}Cs in a control site, and
$^{137}Cs_e$ (Bq/m^2) is the concentration of ^{137}Cs in a study site.

Five percent of the original ^{137}Cs is assumed to have been lost to blowing snow and crop removal; thus, use of the coefficient 0.95. Soil loss ($Mg\ m^{-3}$) is calculated with the following relationship (de Jong et al. 1983):

$$\text{Soil Loss} = {}^{137}Cs \text{ loss} * d * D_b$$

where: d = thickness of sampled layer (m), and
D_b = bulk density ($Mg\ m^{-3}$).

The concentration of ^{137}Cs in depositional locations is not used for estimating accretion; rather, the depth to which ^{137}Cs occurs is used to estimate the depth of soil deposited. The equations used to estimate deposition are as follows:

$$d_d = d_{cs} - 10$$

where: d_d = thickness of soil deposited (m),
d_{cs} = depth to which ^{137}Cs is present (m), and
10 = assumed depth of cultivation (m).

$$\text{Soil Gain } (Mg\ m^{-3}) = dd * D_b$$

Calculation of soil loss by this technique is dependent on several assumptions, the most being that ^{137}Cs was uniformly distributed on the landscape. The ^{137}Cs technique

does not separate the effects of water erosion from wind erosion or rill erosion from interrill erosion.

The use of ^{137}Cs is a relatively new method of measurement of soil erosion and seems to provide an easy and inexpensive method of measuring soil erosion on selected landscape segments (de Jong et al. 1983; Kiss et al. 1986; Pennock and de Jong 1987). Limitations include the assumption of uniform spatial distribution of ^{137}Cs initially, the lack of differentiation between wind versus water erosion and the lack of separation of water erosion processes.

Erosion Pan Studies

The use of soil erosion pans was first introduced by Gerlach (1967) and further discussed by Leopold and Emmett (1967). More recently, Roels and Jonker (1983) used a modified Gerlach trough to estimate the variability of soil erosion on rangelands resulting from rill and interrill erosion, and described the use of erosion pans for estimating soil erosion based on probability sampling techniques.

Soil erosion pans facilitate the measurement of the spatial variability of soil erosion for various slope positions and cultivation patterns. Erosion pans are designed to measure the interrill and pre-rill (Roels and Jonker 1983) components of the soil erosion process, e.g., relatively small scale erosion processes. Soil erosion pan data can be expressed as a probability distribution function describing the amount of soil erosion and the range of soil loss that might be expected for any slope segment. Pans allow an explicit approach to measuring total erosion on a open landscape through judicious placement of the pans. Pans are relatively inexpensive to manufacture and can be installed on different slope segments at different sites.

Results from erosion pans are confounded in that the slope length contributing to the delivery of runoff and sediment to the pan is variable depending on the intensity and nature of the erosive event and the pan's distance from the slope crest. Therefore, estimation of

soil erosion on a landscape basis is difficult. Roels and Jonker (1983) proposed that soil erosion, as measured by pans, can be expressed on a unit width basis as opposed to an areal basis. Rill erosion is not easily measured with pans which have limited capacity to retain runoff water and sediment.

Rill Meter Studies

Rill erosion can be measured directly using a device commonly referred to as a rill meter. The rill meter consists of a series of pins in a fixed frame. The pins are lowered into the cross-section of a rill, perpendicular to the rill, and the cross-seetional area is measured by tracing the height of the pins graphically, photographically or electronically. A series of cross-sectional areas is taken along the length of the rill along with distance measurements. Volume of soil lost from the rill is calculated from the cross-sectional area by length data. This volume of soil can then be converted to mass using bulk density.

The rill meter technique is flexible and easy to use in a variety of field situations. The equipment is inexpensive and results can be obtained quickly, especially if the profile is recorded electronically. Rill meter studies are generally aimed at larger scale erosion than are erosion pan studies. Erosion pans are effective for measuring processes on a scale of 1 to 10 meters whereas rill meter studies can be effective for measuring erosion on a scale of 10 to 100's of meters.

The accuracy of rill-meter data has not been assessed. The placement of the rill meter and the length between cross-sectional areas depend on the judgement of the user. Furthermore, there is no standard method for calculating the volume of soil lost; therefore, the direct comparison of results from different studies may not be reliable. Rill erosion can be estimated using aerial photography and other methodologies; none is as effective as the rill meter for obtaining data quickly and inexpensively.

Landscape Analysis

Topography is an important variable in soil genesis and has a direct influence on the energy and water balance for a given site. Landscape analysis is a technique of evaluating soil properties on a landscape as a function of surface form and slope position. Mermut et al. (1983) used this technique to compare soil properties along cultivated and non-cultivated transects to evaluate erosion, organic matter and nitrogen in a clayey soil in Saskatchewan.

Lanyon (1983) used land surface morphology, as expressed by surface gradient and curvature, to correlate topography with soil properties as observed in the field and laboratory. Pennock and de Jong (1987) measured the influence of slope curvature on soil erosion and deposition on hummocky topography. The susceptibility of land form segments to erosion varied with profile (downslope) curvature, plan (across-slope) curvature and slope gradient. Land form segments were ranked from those with highest erosion to those with highest deposition. Martz and de Jong (1985) measured the relationship of land surface form to soil erosion and deposition on hummocky landscapes; susceptibility to erosion differed with slope curvature and gradient. The majority of sampled sites experienced soil loss; only 11 to 17% of the sites had deposition.

Landscape analysis is a relatively new approach to the quantification of land surface processes. The development of computer programs to calculate the appropriate variables for surface form based on surface elevation has enhanced the ability to develop relationships of surface form to soil properties and processes.

APPROACHES TO MODELING SOIL EROSION

There are many conceptual and mathematical approaches to modeling soil erosion. Kirkby (1980) discussed three approaches: empirical models; physically based, component models; and stochastic models. The USLE is an empirical model based on regression analysis of plot data. Physically based models utilize physical processes of particle detachment and transport in response to inputs of rainfall and overland flow. Equations

derived from experimental data describe the processes of erosion and utilize experimental data. Stochastic models are based on an underlying statistical distribution from which a sample sequence of events is drawn. These models are used in forecasting sediment yield or can be linked with a sediment equation or rating curve. Stochastic modeling has been applied to drainage basin hydrology but not to hillslope plots (Kirkby 1980).

Empirical Models (The Universal Soil Loss Equation)

The Universal Soil Loss Equation (USLE), and its contemporary form as presented by Hudson (1961), is a model of soil erosion based on rainfall, soil properties, slope properties, and agronomic and conservation practices. The USLE is the most widely used method of soil loss estimation and is generally represented as:

$$A = R K L S C P$$

where: A = average annual soil loss,
R = rainfall erosivity factor,
K = soil erodibility factor,
L = slope length factor,
S = slope gradient factor,
C = the cropping management factor, and
P = the erosion control practice factor.

This method of estimating soil erosion (generally referred to as soil loss) has been widely used throughout the world because of its applicability and ease of use. Each of the factors can be calculated or estimated based on the very large data base that has been developed in the United States. Estimates of erosion include rill and interrill erosion collectively, and in general soil is considered lost from the field since soil deposition is not considered. The USLE has proven useful for comparing the relative effects of different management techniques and conservation practices on soil erosion but the estimates of soil loss differ often from the observed sediment yields in rivers and streams. The reason for this discrepancy is most likely related to the uniform application of the results of the USLE

over non-uniform landscapes in which the rate of soil erosion is highly variable and in which significant intermediate deposition can occur.

The USLE was not designed for event-related erosion nor were the processes of rill and interrill erosion separated in the development of the USLE. Slope gradient and length data were considered in the development of the equation; however, slope curvature was not because all experimental plots were taken on planar-sloped (9%) fields. Soil erosion as a result of runoff over frozen soil was not used in the equation because the development work took place primarily in the eastern United States.

Modifications to the equation to take into account processes not included in the original formulation are essentially weighting factors for one or more of the individual factors. Tajek et al. (1985) developed a weighting factor to include soil loss due to snowmelt for Alberta. These types of modifications are useful in adapting the equation for different climatic, soil conditions and management situations but do not elucidate the processes involved in soil erosion and deposition on a landscape basis and are subjective.

In Alberta, most soil erosion is the result of specific meteorological events which include snowmelt and intense spring and summer rainfall. Soil erosion is most likely to occur in situations where the soil is exposed due to cultivation. Landscape form also has a influence on the occurrence of erosion. Rilling occurs on relatively small portions of a landscape and contributes considerably more sediment to depositional locations than does interrill erosion. The presence of eroded knolls suggests that these portions of the landscape are particularly susceptible to soil erosion. Thus, the USLE may not be well suited for landscape studies of erosion and deposition.

Physically Based Models

Meyer and Wischmeier (1969) presented a physically based model of soil detachment and transport (Fig. 1.1). This model has been the focus of the work of several researchers since it was originally published (Foster and Meyer 1975; Morgan 1979;

Khanbilvardi et al. 1983). The model was based on a soil mass balance for laterally-uniform slope segments. A computer program was developed to simulate soil and water movement from the top of a slope to the bottom. Simulation was conducted for two-dimensional slopes without slope curvature. A slope was divided into segments of uniform gradient and soil properties. Each slope segment was evaluated and soil was redistributed based on the relationship of detached material to transport capacity. The authors (Meyer and Wischmeier 1969) were able to simulate soil erosion and deposition for several slope shapes, slope gradients, soil conditions and rainfall intensities with the model. The approach was entirely theoretical and there were no attempts at field validation.

Meyer and Wischmeier (1969) developed relationships for the two detachment and two transport components which were presented as follows:

DR (detachment by rain) = $S_{DR} A_I I^2$

DF (detachment by runoff) = $0.5 S_{DF} A_I (S_S^{2/3} Q_S^{2/3} + S_E^{2/3} Q_E^{2/3})$

TR (transport capacity of rainfall) = $S_{TR} S I$

TF (transport capacity of runoff) = $S_{TF} S^{5/3} Q^{5/3}$

where: S_{DR}, S_{DF}, S_{TR} and S_{TF} are coefficients to reflect soil effects for each of the expressions,

S = slope gradient,

Q = flow rate (subscripts S and E are for start and end of slope segment respectively,

A = the surficial area of the slope segment,

A_I = the area of the increment, and

I = rainfall intensity.

The relationships between detachment and transport were developed from published material.

The conceptual model of Meyer and Wischmeier (1969) proved to be the focus for the development of equations describing each of the components of detachment and transport, e.g., bedload equations appropriate for transport and detachment (Foster and Meyer 1975). The equation of continuity for sediment transport as expressed by Foster

and Meyer (1975) is a mathematical expression of the conceptual model presented in Fig. 1.1:

$$\partial G/\partial x = D_r + D_i$$

where: G = sediment load (weight/time/unit of cross sectional width), including total interrill and rill widths,

x = distance downslope,

D_r = detachment (or deposition) rate of rill erosion (weight/time/unit of total area including rill and interrill areas), and

D_i = delivery rate of particles detached by interrill erosion to rill flow (weight/time/unit of total area).

Foster and Meyer indicated that:

$$D_r/D_c + G/T_c = 1$$

where: D_c = the detachment capacity of the rill flow and

T_c = the transport capacity of the rill flow.

These two equations formed the basis of a simulation of soil erosion in which the predicted results were compared to the observed results from soil erosion plots. The terms D_c, T_c and D_i were treated as independent variables defined by rainfall and runoff characteristics and soil properties. The terms G and D_r were unknowns. The Yalin (1963) equation, which was not developed by the authors, was used to evaluate T_c and D_c. The Smeardon-Beasley critical shear stress relationship (which was not discussed or referenced by the authors) was used to estimate D_c. The authors continued with a theoretical development of closed form representations of the two previous equations. These closed form equations were also used to simulate soil erosion from the plots and the predicted results were very close to the observed results (Foster and Meyer 1975).

Khanbilvardi et al. (1983) developed a computer simulation model of upland erosion based on continuity considerations for sediment transport and on equations describing rill and interrill erosion. The model is an enhanced version of the Meyer and Wischmeier (1969) model with rill and interrill erosion as individual components and with quantitative estimates of soil detachment and transport. The basin under study was divided into regions

of rill and interrill erosion based on the USLE and on equations describing detachment and transport capacity of rill flow. The USLE was used to estimate the sediment load from contributing areas. Comparison of transport and detachment capacity was used to determine the amount of total erosion and deposition for specified rainfall events.

Simulation was initiated by the infiltration equation of Philip (1957):

$$I = St^{1/2} + At$$

where: I = cumulative infiltration,
S = sorptivity,
t = time, and
A is a series expansion coefficient related to hydraulic conductivity at saturation.

Rainfall in excess of cumulative infiltration was calculated at each grid node in the model for each time step based on the Philip equation. Where runoff occurred, rill patterns were calculated based on the elevation matrix for the model. Then the area contributing to rill flow was calculated and the USLE was employed to estimate the amount of erosion from the contributing areas. The R factor of the USLE was adjusted to facilitate modeling individual storms using a relationship developed by Cooley (1980).

Rill detachment was calculated using an equation first presented by DuBoys (1879). This equation took the form:

$$D_c = \psi \tau(\tau - \tau_{cr})$$

where: D_c = the detachment capacity,
τ = the actual shear stress,
τ_{cr} = the critical shear stress from Shield's diagram (Shields 1936), and
ψ = a sediment characteristic factor (Morris and Wiggert, 1972).

$$\psi = 10\ V/d(\gamma_s - \gamma)$$

where: V = flow velocity in rill, and
d, γ_s, and γ are particle diameter, particle density, and fluid density.

This equation was chosen in favour of the one developed by Foster and Meyer (1972) because field calibration of coefficients was not required. Finally, the equation presented by Yalin (1963) was used to predict rill transport capacity:

$$T_c = 600 * d\delta (HB)^{1/2}[1-0.6 / T_{cr}^{1/2}\delta \log(1 +1.66T_{cr}^{1/2}\delta)]$$

where: T_c = the rill transport capacity

d = particle diameter,

H = hydraulic radius,

B = slope steepness,

T_{cr} = critical lift force from Shields Diagram (Shields 1936),

$\delta = (T - T_{cr})/T_{cr}$ (when T is less than T_{cr} then $(T - T_{cr}) \sim = 0$), and

T = HB/1.65d.

This equation was reported by Khanbilvardi et al. (1983) to be theoretically sound and fitted observed data well, according to Foster and Meyer (1972).

These equations were used to estimate soil erosion on a hypothetical basin. Values for sorptivity, the A value for infiltration, elevation data and parameters for the USLE were estimated for each grid node in a 10 x 10 ft matrix.

The Khanbilvardi et al. (1983) erosion model seems to be the first that attempted to separate rill and interrill erosion on an areal basis using elevation data. Parameters for the USLE can be changed and rainfall inputs can be modified for subsequent runs of the model. This model is deterministic: soil erosion was assumed to be constant at each grid node and for the contributing areas from run to run if the input parameters were not changed. Parameters like sorptivity theoretically change with time due to changes in antecedent soil moisture at the time of rain initiation and thus in reality similar rain storms would not always erode in the same manner.

In subsequent publications (Khanbilvardi and Rogowski 1984; 1986), the applicability of the model to larger watersheds was examined. Several modifications to the original model were effected to facilitate larger scale studies. A method of estimating sorptivity S and the series expansion coefficient A were developed based on the readily

available values of water content at 1/3 and 15 bars. Secondly, a relationship between the soil erodibility factor (K) of the USLE and runoff/infiltration ratio was proposed to predict rill sources since in larger areas the original relationships relating rill initiation and transport to flow regimes (laminar for interrill areas and turbulent for rill areas) could not be applied. Antecedent moisture conditions were not considered in any of the modeling. The model was validated for two watersheds in which total sediment yield data were available.

Rose (1985) reviewed physically based erosion and deposition models, the conceptualization of erosion and deposition processes and the modeling thereof, and proposed an analytic solution for modeling erosion and deposition on a plane surface. Physically based models have a sound basis in theory but are difficult to apply in practice. In most circumstances microtopography, surface cover, and other relevant parameters are either assumed not to exist or are considered constants which by definition are invariant in a simulation. The separation of rill and interrill processes is possible in a mathematical simulation but applicable to field conditions which are characterized by microtopography, surface cover and highly variant slope patterns is not realistic.

The Water Erosion Prediction Project (WEPP) is a multi-agency project scheduled to replace the regression vs stochastic based USLE with a physically based continuous simulation model using modern hydrologic and erosion science (Lane and Nearing 1989). The current version of WEPP is reported to account for soil loss and soil deposition on hillslopes, and the project includes the future development of watershed and grid versions. The model includes ten components: weather, snowmelt and frozen soil, infiltration, surface runoff, soil, water balance and percolation, plant growth, hydraulics and overland flow, irrigation and erosion. The WEPP model is implemented as a hillslope profile erosion model and as such does not take into account complex surface form, although it is designed to account for temporal and spatial variability in soil properties, cropping patterns, crop growth and hydrology. WEPP is designed to account for rill and interrill erosion using a steady-state sediment continuity equation (Foster et al. 1989).

Difficulties with physically based models are often related to the number of parameters which must be evaluated for a given situation. The temporal and spatial variability of the soil erosion process is considerable and thus the number of parameters required for simulation is considerable. The relationship between infiltration and runoff is, on its own, a complete field of study and to incorporate all of the required parameters is beyond the scope of a simple erosion model. If spatial and temporal variations of the parameters necessary to model erosion cannot be measured accurately and cost effectively, then those parameters must be estimated in some way. Hence, assumptions about the relationship of infiltration and runoff are often made to facilitate the solution of the erosion model.

Landscape Based Models

Bork and Rohdenburg (1986) discussed methods for estimating initial conditions and boundary conditions for distributed hydrological and agroecological catchment models. The authors recognized the need to estimate these conditions for each element in three dimensional finite difference grids based on a limited number of observations within the catchment under survey. They proposed the use of a Digital Relief model to compute land surface form (gradient, curvature, aspect), a Digital Sediment and Soil model to represent soil and sediment properties (horizon thickness, texture, structure) and a Land Use Data Processor to compute land use information (tillage direction, plant height) from maps or remotely sensed data. Bork and Rohdenburg did not explicitly address the links or relationships between each of the models they described. The links are implied in that soil texture and moisture content were highly correlated and that several predictors were useful in estimating moisture content. The 'laws of geomorphology and soil development' were used to classify unsampled pixels in the model for soil properties. Fully automatic classification systems like kriging were found to be unsatisfactory; however, 'a simple

interpolation procedure provided weighted mean values, taking into account the spatial distribution of sediments and soil horizons in neighboring grid elements' was used.

The authors did not give much detail on the equations used for calculating surface form, soil properties and land use. They presented maps of computed soil moisture based on field measured values, land cover maps, slope properties derived from elevation maps and soil maps also based on spatial interpolation of measured field values. This approach to modeling was not explicitly designed for erosion studies but the authors noted that work was underway to add parameters to facilitate erosion modeling. This approach to hydrological modeling provides a conceptual basis for modeling the temporal and spatial variability of soil erosion.

Roels (1984) developed a model of soil erosion based on the conceptual model of Meyer and Wischmeier (1969) in which rainfall and runoff erosivity factors were used to develop equations for each component of soil erosion. The method and analysis of Roels was based on measuring the variability of soil erosion in the field in relation to rainfall. The model presented was as follows:

$$G_r = a\,REF + b$$

$$G_{pr} = c\,REF + d$$

$$\text{Log } G_{ir} = e \text{ Log } EAIM + f$$

$$\text{Log } G_s = g \text{ Log } EI_{30} + h$$

where: G_r = rill erosion,

G_{pr} = pre-rill erosion,

G_{ir} = interrill erosion,

G_s = rainsplash erosion,

EAIM = the product of the excess rainfall amount (EA) and the maximum 5 minute intensity (IM) for the storms measured,

EI_{30} = the product of rainfall kinetic energy and the maximum 30 minute intensity, and

a to h are coefficients.

REF, the runoff erosivity factor, is represented as:

$$REF = Q\,PD^{1/3}\,A^{-1}$$

where: Q = the runoff volume,

PD = peak discharge, and
A = unit area.

Roels used regression analysis to develop values for the coefficients in each of the four processes based on the field data collected for nine storms. The analysis was based on different source locations (upper slope versus lower slope) and grouped source locations. This method of modeling accounts for the spatial variability of the processes of soil erosion. Roels recognized that this approach does not explicitly account for many factors affecting each of the processes.

Research Needs

None of the approaches to measuring or modeling erosion, with the possible exception of ^{137}Cs (Pennock and de Jong 1987), account for complex surface form (slope curvature as well as gradient and the interaction between landscape elements), the temporal and spatial variability of erosion or deposition on the landscape. Most approaches develop equations or relationships for fixed slope segments or plots and do not incorporate the relationship of neighboring slope segments and their impact on the erosional processes for the slope segment under consideration. Commonly, the landscape on which erosion occurs is ignored in favour of working with small segments of the landscape such as slope segments.

HYPOTHESES

1. Soil erosion can be measured and modeled in an open landscape fashion which incorporates complex slope form, microtopography, soil properties and variable amounts of erosion.
2. Soil erosion is controlled, in part, by the land surface form as described by slope properties such as slope gradient, slope curvature and measures of flowpath. These slope properties may have a marked influence on the movement of water on the soil surface and thus the redistribution of soil

materials. Land surface form can be used in conjunction with soil properties to model soil redistribution on the landscape.

3. The amount of soil erosion, on a field basis, is not a fixed value but is a population of values having characteristic measures such as mean and variance. This population can be sampled and the characteristic measures determined by field studies and through the development of probability distribution functions.

OBJECTIVES OF THE RESEARCH

1. To measure the characteristics of soil redistribution on agricultural landscapes using ^{137}Cs, soil erosion pans, the rill meter and landscape analysis.
2. To determine the relationship between soil redistribution and land surface form.
3. To develop a conceptual approach to modeling soil redistribution on agricultural landscapes that incorporates the spatial and temporal variability of soil redistribution.

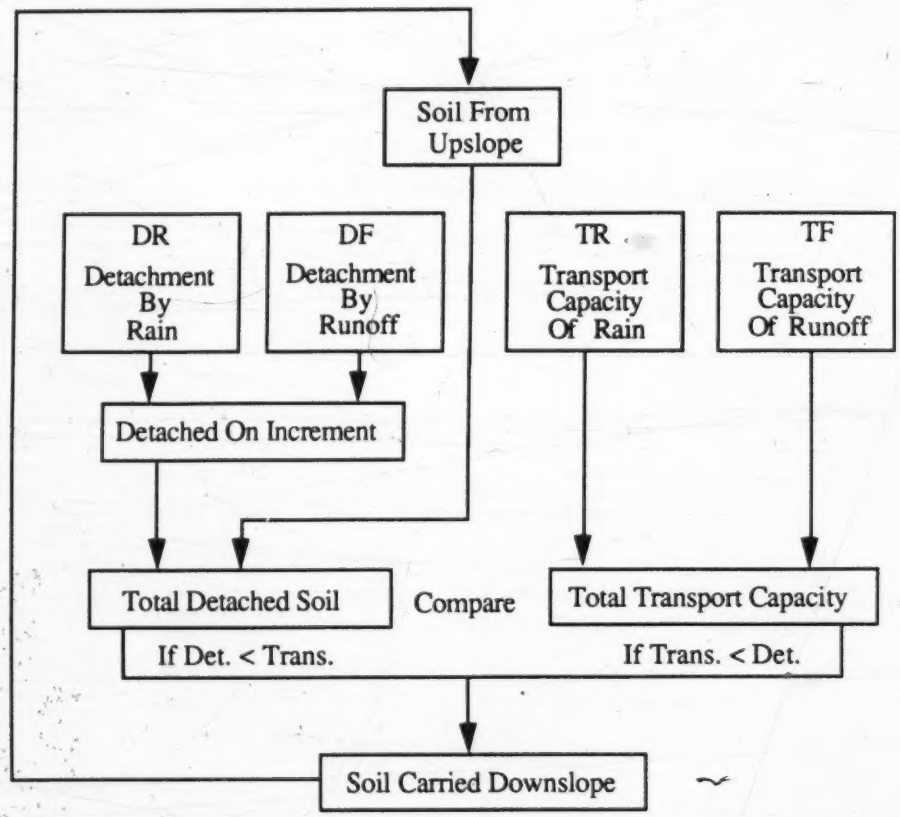

Figure 1.1 Schematic diagram of transport and detachment processes (after Meyer and Wischmeier 1969).

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CHAPTER 2

EXPERIMENTAL DESIGN

INTRODUCTION

Many erosion studies use a single technique for the measurement of processes that occur at several scales in space and time. This project is unique in that soil erosion is being considered in an open landscape fashion and in that several measures of soil erosion are being used to assess the severity of the process. Soil erosion was measured at several scales as it occurred on the landscape. The purpose of this chapter is to provide an overview of research methods and thesis organization.

EXPERIMENTAL DESIGN

Open Landscape Approach to Measuring Water Erosion

The term 'open landscape' approach is used throughout this dissertation. The term has been coined in this study to describe research methods and an approach to the study of landscape processes that do not restrict the location of study with artificial boundaries or impose artificial treatments to simulate the processes under study. On the other hand, 'bounded landscape studies' (also coined in this study) involve measurement techniques wherein boundaries are placed on specific landscape elements, e.g., a mid-slope position for the purpose of studying processes in that specific location.

In an open landscape approach, it is necessary to define characteristic slope elements that can be sampled or monitored during the occurrence of erosive meteorological events. The concept of measuring processes 'in situ' and considering their spatial and temporal variability is fundamental to the open landscape approach, as is the concept of using existing soil and landscape properties to quantify or infer soil forming processes.

Howitt and Pawluk (1985a, b) discussed the concept of using static and dynamic techniques in the study of soil forming processes. Static techniques were used to infer the occurrence of a process or quantify the magnitude of a specific process using soil properties. ^{137}Cs, landscape analysis and digital terrain modeling (static techniques) were used in this study to quantify the magnitude of erosion processes, infer the occurrence of soil erosion processes and quantify the land surface form respectively. Dynamic techniques are used to measure soil forming processes 'in situ' allowing for spatial and temporal variability of the meteorological events causing changes in the spatial and temporal variability of the soil landscape. Erosion pan and rill meter studies were used in this study to make 'in situ' measurements of erosional processes in relationship to land surface form allowing for the spatial and temporal variability of these processes.

The open landscape approach to measuring and modeling land surface processes necessitates purposive sampling techniques as compared to statistically defined sampling techniques. For example, the selection of pan locations or soil sample locations must be on the basis of the processes being studied and not on the basis of random selection. Purposive sampling is contrary to statistical theory and makes the use of accepted statistical analyses difficult because of the issue of bias. Did the experimenter make measurements that were known to influence the outcome of the statistical analysis?

The study of landscape processes is open ended (as compared to a closed plot study) and a researcher must use accepted theory and empirical knowledge of landscape processes in experimental design and data analysis. This study was designed to be open ended in the quantification of erosional processes. The processes under study should not be contained within an artificial plot boundary. The occurrence of these processes is bounded by naturally occurring land surface form (hills, valleys, depressions, break points) as measured with slope gradient, curvature and other elevation derivatives; anthropogenic boundaries such as roads, fence lines; and by naturally occurring meteorological events.

Experiments must be designed to take into account the spatial and temporal variability of the phenomenon under study and in this case an open landscape approach is necessary.

The foregoing discussion on measuring and modeling soil erosion was incorporated into an experimental design which includes field experimentation and data analysis techniques (Fig. 2.1). The field component was designed to obtain information on the amount of rill and interrill erosion and to quantify soil properties on erosional and depositional portions of the landscape. The analysis techniques were designed to evaluate soil erosion processes and soil properties in relation to land surface form as characterized by digital terrain derivatives.

Field Methods

Seven field sites were established in 1985 in east-central Alberta (Fig 2.2). These sites (WD, HN, KZ, YS, HL, MC, EO) were chosen to be representative of characteristic landforms, soil parent materials and land management in the region and were selected to allow comparison of adjacent cultivated and non-cultivated fields. The EO site was dropped following ^{137}Cs analysis because it did not have an adjacent cultivated field within 5 km's. The non-cultivated fields had not been cultivated since the mid 1950's and, with the exception of the MC site, all sites were grazed annually. Recording meteorological sensors and data loggers were established at six sites in order to evaluate the nature and severity of meteorological events. Sensors included a tipping bucket rain gauge, an accumulation rain gauge, an anemometer (direction and speed), pyranometer, thermistor for air temperature and a relative humidity sensor. Sensors were monitored throughout the whole year using an Omnidata data logger and the sites were visited every two weeks or in response to rainfall events and/or springmelt events to collect data and evaluate any erosion that may have occurred.

Soil samples were collected from all of the sites for ^{137}Cs and for soil properties in top, upper, mid, lower, toe and depressional slope positions. Non-cultivated sites were

sampled to determine the base levels of ^{137}Cs. These data were collected in order to establish an estimate of the 'average annual rate of soil erosion (or deposition)' since the mid 1950's when ^{137}Cs was introduced to the atmosphere. This average annual rate is different from the average annual rate as determined with the USLE in that it is a measured value and based on field measurements at the site of interest. The amount of erosion or deposition can be compared to measured erosion and deposition during springmelt to provide corroborative information and input for modeling.

All sites were monitored for erosion from 1985 to 1988 by visiting them regularly and collecting both meteorological data and erosion pan/rill meter data as required. Land management at each site was controlled by the producer-owner participating in the project. Two sites (YS, WD) were instrumented to measure erosion in response to rainfall and springmelt between 1985 to 1988. They were summerfallow fields, considered most prone to erosion. Two techniques were employed to measure soil erosion in response to erosive meteorological events. The first was the use of erosion pans as described by Roels and Jonker (1983) to measure the interrill component of the soil erosion process. This is based largely on the conclusions of Roels and Jonker (1983) who found that the smallest standard errors were obtained by sampling interrill erosion and measuring total rill erosion separately. Soil erosion pans were installed to sample interrill erosion in different slope positions and on different gradients in relation to the pattern of cultivation. Pan locations were selected at each of the two sites (YS,WD) to represent the range of slope gradients and to obtain data for upper, mid and lower slope positions. The pans were installed in groups of three to establish within-site variability and provide enough data to evaluate between-site variability. Groups of pans were installed 'en echelon' as described by Roels and Jonker (1983) to quantify soil erosion on slope positions.

The rill meter was used to measure soil erosion. In cultivated agricultural fields, the identification of potential rill patterns prior to a storm is impossible due to cultivation which

destroys established rill patterns. Thus, in order to measure total rill erosion, the rill meter technique must be employed after the rills have formed.

All six sites were aerially photographed to establish a basis for developing digital elevation models for the sites. Ground targets were installed prior to the aerial photography to ensure that corrections for the tilt and yaw of the aircraft could be made and to provide a basis for relating to real world coordinates. The ground targets were surveyed with respect to one another so that the aerial photography could be rectified with respect to the actual ground surface. Only the photographs from the YS site were analyzed to produce a matrix of elevation data relative to the targets. A digital elevation model (DEM) was developed photogrammetrically for the YS site.

The YS site was chosen for detailed study of soil erosion as reflected by soil properties and landscape analysis. Soil sampling at this site was conducted more intensely than for the other sites. Five soil sampling transects were established perpendicular to the contour of the site. Approximately 15 soil profiles were described on each transect and samples of the Ap horizon of each profile were taken for laboratory analysis. Each of the profiles was classified in the field as being eroded (Ap < 15 cm or mixing with Bm in lower Ap), intermediate (15 cm < Ap < 20 cm) and depositional (Ap > 20 cm). Classification was based on the average depth of cultivation in the region (15 cm) and the assumption that once B horizon material is included in the Ap, surface soil loss has occurred. The location of each sample site was determined in relation to the target sites for aerial photography using land survey equipment. This data set was used with the digital terrain data to evaluate the relationship between soil properties and surface form.

The field component of this project focussed on acquiring data on the occurrence of erosion on the landscape in a manner that would permit analysis of erosion in relation to land surface form. The field component of the study was intended to establish the variability of the amount of soil erosion for different slope segments, leading to a

conceptual model of erosion processes and input data requirements for simulating water erosion on a landscape basis.

Analytical Methods

In general, the approach to analyzing field data was to first develop descriptive statistics (mean, standard deviation, frequency distribution, skewness and kurtosis) to establish the nature of the data being analyzed. This was followed by a spatial analysis of the geographic distribution of means, classes of variables (rill versus interrill for example) and then by statistical analyses to compare and contrast the relationships between variables (surface form versus rill patterns for example).

The means of ^{137}Cs were compared for within-site variability (slope position) and between-site variability. Correlation, regression and analysis of variance were used to study relationships between ^{137}Cs and soil properties and to compare between-site differences. Duncans Multiple Range Test was used to compare means.

Roels (1984) presented a method for evaluating and modeling net erosion measured in different slope positions. The field data on amounts of erosion and runoff can be used to develop probability distribution functions for different slope configurations. These functions can then be used in conjunction with random number generator for a Monte Carlo simulation of soil erosion on the landscape. Erosion pan data were used to calculate mean soil loss values for each slope position being monitored and for each event that took place between 1985 and 1988. The amount of soil loss from rill erosion was calculated from the cross-sectional area and length measurements taken in the field. The area of contribution and amount of rill erosion was compared to the area and amount of interrill erosion. The area of soil deposition in the basin was also calculated and volume of soil deposition compared to that "lost" through rill and interrill erosion.

Photogrammetric techniques were employed to create a DEM of the YS site. The DEM had a vertical resolution of 10 cm on a 4 x 4 m grid. The digital elevation grid was

used to calculate the first and second spatial derivatives (slope gradient and slope curvature (in two directions)) and slope aspect using finite difference techniques (Eyton Pers. comm.). The calculations employed were based on a 3 x 3 elevation matrix.

The digital elevation model that was developed for the YS site was used to produce matrices of slope gradient, downslope curvature, across-slope curvature and flowpath as calculated using Eyton's (Pers. comm.) techniques. These data matrices were used in the statistical analysis of the field data (locations of rill and interrill erosion, deposition and soil properties) to evaluate relationships between surface form and erosion.

The locations of rill patterns, locations of deposition and location of interrill erosion were merged with the digital elevation model. The relationship between surface form and the amount of erosion measured with erosion pans and the rill meter was evaluated statistically to compare rill, interrill and depositional grid elements. Analysis of variance and Duncans Multiple Range Test were used to make the comparisons and discriminant analysis was used to evaluate the relationship between erosion process (rill, interrill and deposition) and surface form.

The YS site was intensively soil sampled to identify soil properties that characterize erosional, depositional and intermediate portions of the landscape. Data from soil sampling and the digital elevation model were merged to identify sampled grid elements and develop data sets to evaluate the relationship of soil properties to the land surface form. Analysis of Variance and Duncans Multiple Range Test were used to compare grid elements classed as being eroded, depositional or intermediate. Discriminant analysis was used to evaluate the relationship between soil properties and surface form.

The results of these analyses provided a mechanism to extrapolate results from sampled grid elements to all of the grid elements in the digital terrain component. By linking measured field processes with the digital terrain model, data on the locations of soil erosion or deposition can be compared with measures of surface form and soil properties.

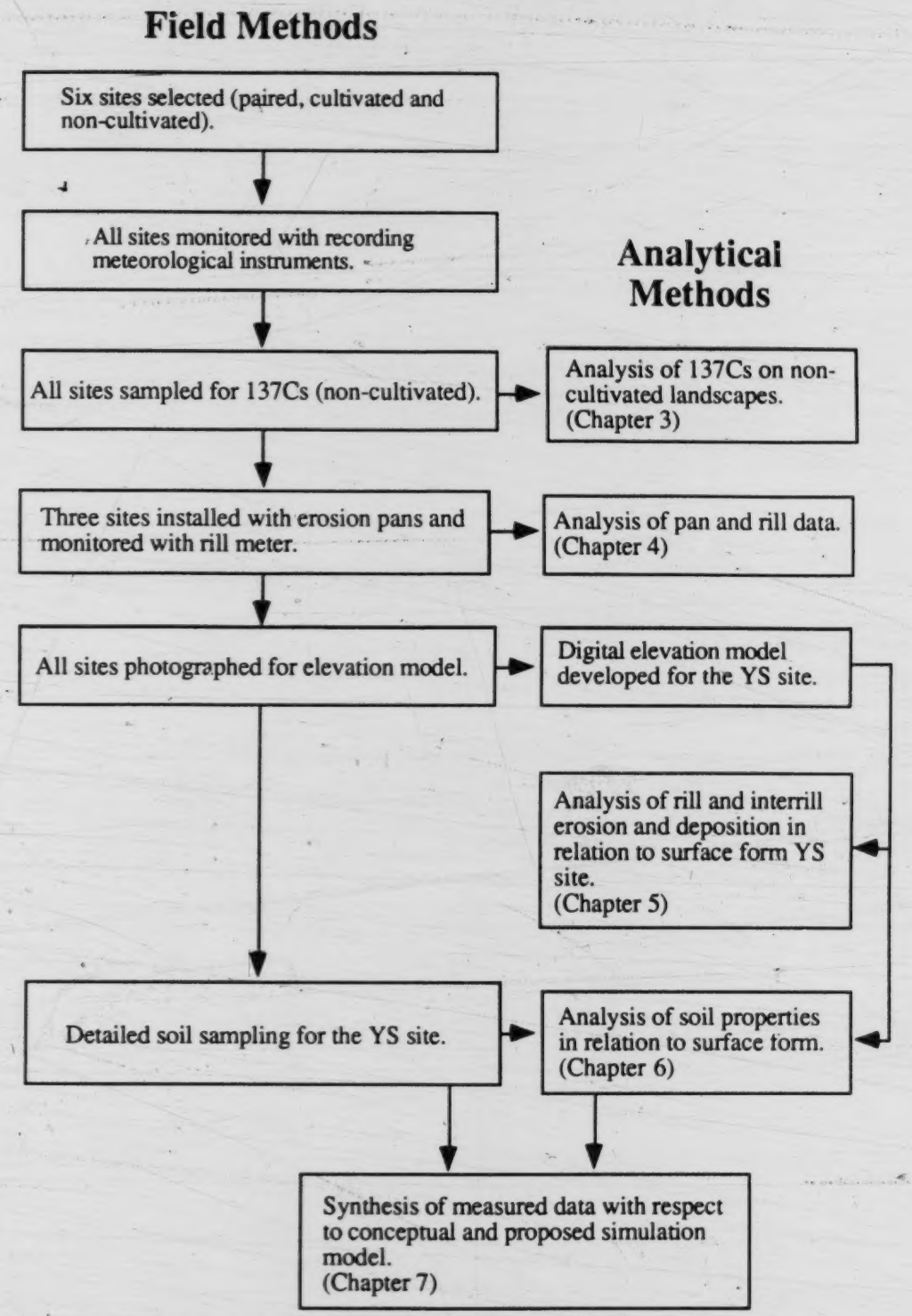
Field Methods
Six sites selected (paired, cultivated and non-cultivated).
All sites monitored with recording meteorological instruments.
Analytical Methods
All sites sampled for 137Cs (non-cultivated).
Analysis of 137Cs on non-cultivated landscapes. (Chapter 3)
Three sites installed with erosion pans and monitored with rill meter.
Analysis of pan and rill data. (Chapter 4)
All sites photographed for elevation model.
Digital elevation model developed for the YS site.
Analysis of rill and interrill erosion and deposition in relation to surface form YS site. (Chapter 5)
Detailed soil sampling for the YS site.
Analysis of soil properties in relation to surface form. (Chapter 6)
Synthesis of measured data with respect to conceptual and proposed simulation model. (Chapter 7)

Figure 2.1 Flow chart of research methods and organization of thesis (Chapter 2).

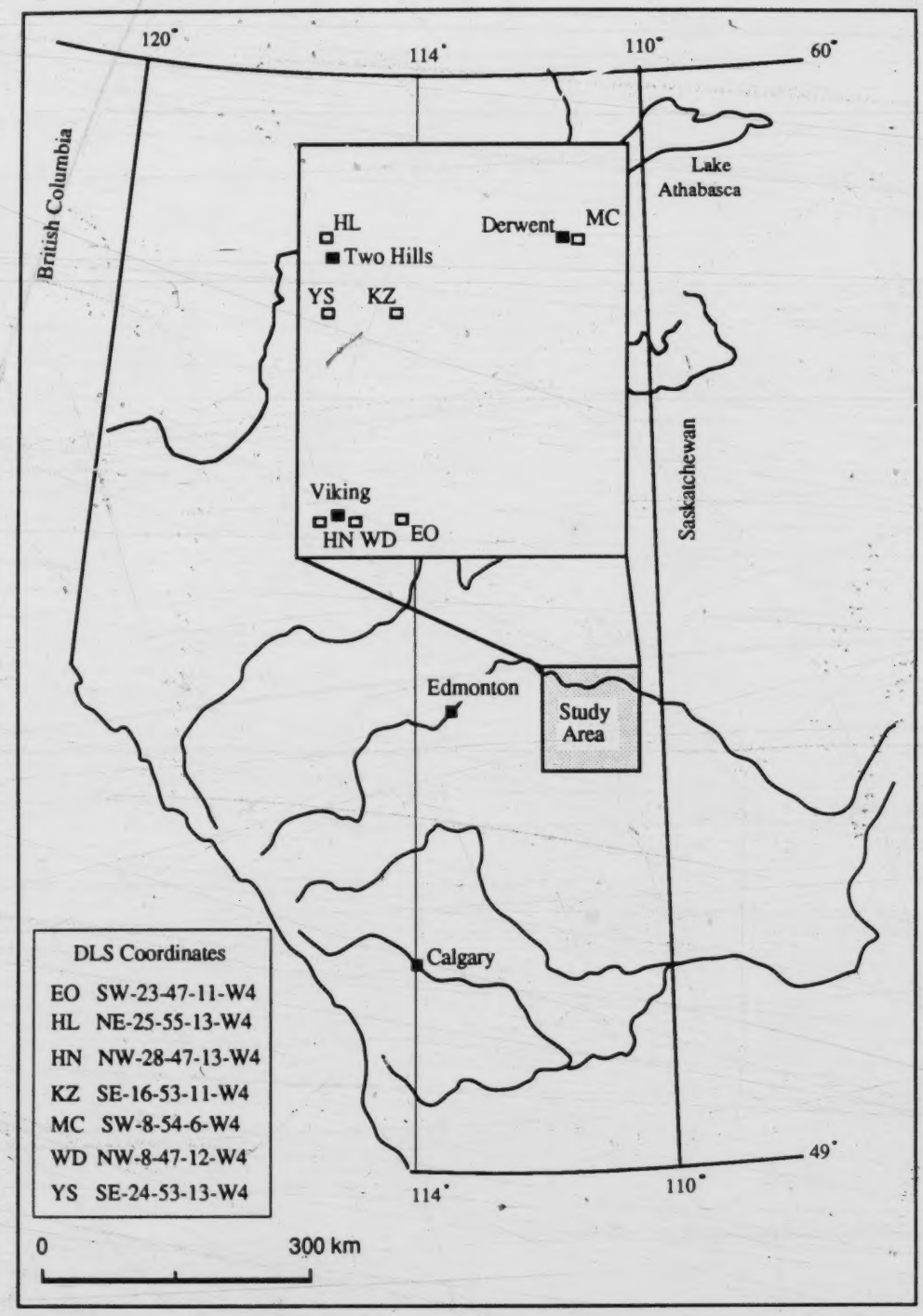

Figure 2.2 Locations of study sites in east-central Alberta.

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CHAPTER 3

SPATIAL VARIABILITY OF ^{137}CS ON NON-CULTIVATED LANDSCAPES IN EAST-CENTRAL ALBERTA AND ITS EFFECT ON SOIL EROSION ESTIMATES

INTRODUCTION

Soil erosion is a persistent problem in east-central Alberta but few studies to date have attempted to quantify the severity and extent of erosion. These few studies on soil erosion in Alberta have adopted the use of bounded plots (Toogood 1963; Chanasyk and Woytowich 1983; Chanasyk and Woytowich 1986) for measuring soil loss. These studies focussed on the dynamic aspects of soil erosion in response to specific meteorological events on selected portions of the landscape. Plots are a well established and accepted method of measuring soil erosion but the results are limited in their applicability over the land surface. Plots are generally established on planar slopes of a specified gradient and rarely on convex upper slopes or concave toe slopes. Hence plot studies can only be considered to be representative of specific portions of the land surface and extrapolation to a larger area is difficult (Boughton 1967; Hayward 1967; Roels 1985). Most estimates of regional soil erosion for the plains region of Western Canada (Prairie Farm Rehabilitation Administration 1983; Tajek et al. 1985) are based on the Universal Soil Loss Equation (USLE). In these regional studies, soil loss is assumed to occur uniformly across the landscape based on a rainfall factor, soil erodibility, average slope length and gradient, a cropping factor and an erosion control factor.

Deposition is an integral part of the soil erosion process and estimates of erosion, either by plot study or using the USLE, generally ignore the fate of eroded material. A technique which would allow the estimation of erosion and deposition at many locations on the landscape in terms of slope position (crest, upper, mid, lower, depressional), slope

aspect and slope gradient would provide an excellent tool for estimating the severity, extent, and impact of soil erosion on a broader scale.

The radioisotope ^{137}Cs has recently been used to estimate the rate of soil erosion on landscapes in Western Canada (de Jong et al. 1982; 1983). Fallout of ^{137}Cs began in the mid-1950's as a result of the atmospheric testing of thermonuclear devices. The radioisotope is a fission product of either uranium or plutonium and has a relatively long half life of 30± 0.2 years. The strong adsorption of ^{137}Cs on soil particles is the characteristic which makes ^{137}Cs desirable as a tracer of soil erosion. The concentration of ^{137}Cs can be measured for any slope position, gradient or aspect and therefore might be an excellent tool to estimate the severity and extent of erosion on the landscape. Furthermore, the amount of deposition can be calculated by determining the depth to which ^{137}Cs occurs in depositional locations.

One technique of calculating soil erosion is using ^{137}Cs, measuring the base level of the isotope on non-cultivated landscapes (control) and comparing it with the level on eroded landscapes. Soil erosion is calculated using the equations presented by de Jong et al. (1982):

$$^{137}Cs \text{ loss} = [0.95^{137}Cs_c - {}^{137}Cs_e] / 0.95^{137}Cs_c$$

where: $^{137}Cs_c$ is the average concentration (Bq/m^2) of ^{137}Cs in the control, and

$^{137}Cs_e$ is the average ^{137}Cs (Bq/m^2) present in the eroded site.

It is assumed that 95% of the original ^{137}Cs remains on the non-cultivated landscape; the 5% loss is assumed to be a result of redistribution due to blowing snow or runoff.

Soil loss is estimated by:

$$\text{soil loss } (kg/m^2) = {}^{137}Cs \text{ loss} * d * D_b$$

where: d is the thickness of the sampled horizon (m), and

D_b is the bulk density of the sampled horizon (kg/m^3).

The assumptions that the fallout of ^{137}Cs was uniform on the landscape and that redistribution of ^{137}Cs is entirely the result of erosion are fundamental to the application of

this method. With the exception of the work of de Jong et al. (1982; 1983), few studies have assessed the variability of ^{137}Cs on non-cultivated landscapes in Canada. Kiss et al. (1988) discussed the distribution of ^{137}Cs in southern Saskatchewan and concluded that background ^{137}Cs activity levels for erosion studies must be based on local sampling of non-cultivated soils. Considerable variability in background ^{137}Cs activity levels was reported for the region. Attempts have not been made to evaluate the implications of site variability of background ^{137}Cs activity levels on subsequent calculations of soil erosion on adjacent, cultivated fields. The objectives of this study were: (1) to evaluate the variability of the base level of ^{137}Cs on non-cultivated landscapes in east-central Alberta in relation to slope position, gradient, and soil properties to determine factors affecting levels of ^{137}Cs, (2) to assess the implications of base level variability on soil erosion predictions, and (3) to provide estimates of soil erosion on cultivated landscapes in east-central Alberta using ^{137}Cs.

MATERIALS AND METHODS

Seven study sites, representative of the soils and landforms in east-central Alberta, were selected. Local district agriculturalists and farmers were consulted in site selection. All of the sites were located in the Counties of Two Hills and Beaver, in an area of approximately 4,000 km^2 bounded by the towns of Viking, Two Hills and Derwent, approximately 90 to 200 km east of Edmonton (Fig. 2.2). The sites have been in pasture since the early 1950's or were never cultivated.

At each site, adjacent cultivated and non-cultivated, downslope transects were established for sampling and calculation of soil erosion. Six slope positions were identified on each of the transects at six of the sites and four slope positions were identified at a seventh site. Several severely eroded knolls were sampled at the WD site to determine the highest soil erosion values for that site. Three sites (WD, YS, HN) were subsequently

resampled on different slopes in an attempt to reduce the coefficient of variability for ^{137}Cs distribution at these sites.

Each slope position on each transect was sampled in triplicate, to the base of the Ah horizon, including the litter layer. The samples were obtained by cutting equal sized (15 x 15 cm) squares of soil material to the base of the Ah horizon using a field knife and tape measure. If more than 15 cm of Ah were present at any given slope position, separate samples were taken from the 0 to 15 cm depth and in 5 cm increments thereafter to the base of the Ah. The three replicates were bagged and analyzed separately for ^{137}Cs.

The core method was used to obtain triplicate bulk density samples in selected slope positions (crest, mid and depressional). The cores were 7.6 cm in diameter and height and were obtained by manually hammering a coring device into the soil and then removing and bagging the soil core. The bulk density samples were also analyzed separately for ^{137}Cs to provide corroborative evidence on the within-site variability of the base level activity of ^{137}Cs. Values of bulk density were used to calculate ^{137}Cs activities on an area basis for the sampled Ah horizons by using the average bulk density value from the respective or closest slope position.

The samples were dried, ground to pass a 2 mm sieve, then placed in Marinelli beakers at a uniform density. Care was taken to ensure that cross contamination of samples during the grinding process did not occur.

The method of de Jong et al. (1982) was used to determine the concentration of ^{137}Cs in the samples collected. An ND-66 Multichannel Analyzer connected to a high purity Ge crystal detector housed in a lead castle was used to measure the area under the gamma photopeak at 0.659 MeV. Concentrations of ^{137}Cs (Bq/kg) were calculated using the equations of de Jong et al. (1982). Modifications to the coefficients of these equations were made to take into account a slightly different geometry related to the sample container and detector. Specifically, the surface area of detection was larger than that of de Jong et al. (1982); therefore, the effective thickness (Xe) was taken as:

$$Xe = 0.0047 * \text{Volume of sample}$$

and the volume of sample was calculated as:

$$V = 96.42 * h - 342.67$$

where: h was the height of sample in the Marinelli beaker.

A standard curve was developed by combining a group of samples with no detectable ^{137}Cs and spiking subsamples of the combined sample with known aliquots of ^{137}Cs. The standards ranged in concentration from 4 to 60 Bq/kg. The relationship of actual ^{137}Cs in the sample to the amount of ^{137}Cs estimated with the ND66 was linear and described by the relationship:

$$^{137}Cs_{\text{counted}} = 0.37 + 0.92 * {}^{137}Cs_{\text{actual}}$$

with a correlation coefficient of 0.99.

Particle size distribution of all soil samples was determined by the pipette method; pH using the saturated paste method with water; exchangeable Na, Ca, Mg, K, and total exchange capacity using ammonium acetate extraction; organic carbon by Leco furnace; nitrogen by the Kjeldahl method, as per McKeague (1978).

Statistical analyses were performed using the SAS statistical package. Proc Univariate was used to develop descriptive statistics, test for normality, develop frequency distributions, stem and leaf analysis, box plots and histograms for ^{137}Cs for each site and for all sites combined. Analysis of variance, correlation and regression analysis were performed with Proc GLM, Proc CORR and Proc STEPWISE respectively. Duncans multiple range testing was performed with Proc GLM.

A Monte Carlo simulation was developed to model the mean and variance of estimated soil loss distribution based on the mean and variance of background ^{137}Cs activity and to quantify the variability in soil erosion estimates if the variance of base level is taken into account. The simulation was run for the WD site which is characterized by severely eroded knolls with lime carbonate to the soil surface. The simulation (available from the author) was developed using a FORTRAN program. The International

Mathematical and Statistical Library (IMSL) subroutine GGNML was used to generate a set of 100 pseudo-normal random numbers with a mean of 0 and standard deviation of 1 which were converted into ^{137}Cs data units by multiplying the random number by the standard deviation and adding the mean of the sampled population. These data were used to simulate the range of base levels of ^{137}Cs in the soil loss calculation to develop a set of estimated soil loss values. The SAS procedure UNIVARIATE was used to produce descriptive statistics of the estimated soil loss values.

RESULTS AND DISCUSSION

A brief description of the sampled landforms is contained in Table 3.1. A given site's descriptor is an abbreviation of the land owner's name.

^{137}Cs Activity in Ah Horizons

The ^{137}Cs activities for the sampled non-cultivated horizons were characterized by considerable variance within each slope position, between slope position and among sites (Table 3.2). Means ranged from 950 to 3804 Bq/m^2 for all slope positions and from 963 to 2423 for three slope positions (Table 3.3). The coefficient of variation (CV) for each slope position ranged from 6% to 118%. The highest coefficients of variation were associated with sites that had either one very low value for ^{137}Cs in relation to the other two values or a range of values from low to high. Data for cultivated transects are not presented because the variability measured in non-cultivated settings was too great to allow comparisons to be made between the two.

The greatest variance among slope positions occurred at the YS site where very low values (compared to all sites) of ^{137}Cs were measured in the crest, upper and mid slope positions with very high values in the lower and depressional slope positions. The trend at the YS site and at the EO, WD and HN sites was an increasing concentration of ^{137}Cs downslope, which suggests redistribution of the tracer on the landscape. de Jong et al. (1983) noted higher concentrations in the lower slope positions on cultivated slopes but not

on non-cultivated slopes. The opposite trend in concentration downslope was noted at the MC and KZ sites, but with no apparent downslope trend at the HL site. Thus, either several processes are operating on the landscape or the degree of redistribution is more pronounced at some sites than at others.

Resampling of several sites on different slope transects in an attempt to reduce the CV for the sites did little to clarify the base level of ^{137}Cs on the landscape or to elucidate the reasons for such variability. At the WD site, resampling resulted in a mean of 2739 Bq/m^2, a standard deviation of 1067 Bq/m^2 and a CV of 40% for 7 samples in mid and upper slope positions. The mean from resampling was 24% higher than the mean based on the first sampling. Resampling at the other sites also produced different values for the mean and high CV's. No consistent trend (either higher or lower values) was noted for the means from resampling.

Preliminary analysis using stem and leaf analysis and box plots revealed several outliers to the main data set which were either very high or very low in ^{137}Cs activity. These data were removed from the analysis because they could not be explained by recounting the sample, they were inconsistent with the published literature and because outlier data points distort most parametric statistical analyses.

The means, standard deviations and CV's for the non-cultivated landscapes were calculated for each site including all slope positions and for just the crest, upper and mid slope positions (Table 3.3). The mean for all slope positions ranged from 950 Bq/m^2 at the KZ site to 3804 Bq/m^2 at the YS site, which were only 12 km apart. The very high value at the YS site was skewed markedly by very high concentrations measured in the depression and lower slope position. The lower, toe and depressional slope positions are those in which some form of accumulation is expected both in non-eroded and eroded landscapes. Since these locations would be subject to deposition rather than erosion, the means for each site were recalculated using just the crest, upper and mid slope positions. The result of using three slope positions was a reduction of the mean at four sites (EO - 13.3%, HN -

5.3%, WD - 14.8%, YS - 50.8%), an increase at the MC site (+22.6%) but essentially no change at the KZ site (+1.4%) or the HL site (+1.8%). The CV at each site was reduced by considering only three of the slope positions (absolute differences by site: EO - 20%, HN - 10%, KZ - 27%, MC - 4%, WD - 7% and YS - 25%), with the exception of the HL site where an increase in CV of only 2% (absolute) occurred. The pooled data for the three slope positions for all sites combined were close to being normally distributed based on histograms, frequency distributions and values for skewness and kurtosis. The data for individual sites approximated normal distributions but the number of data points at each site was lower than desirable for distribution testing.

Based on analysis of variance of the data set for three slope positions, followed by Duncans Multiple Range Test, the KZ site was statistically different from the WD, HN and MC sites (Fig. 3.1). There were no statistical differences among the other sites. The lack of statistical separation of sites is related to the large variance associated with each mean rather than the value of the mean itself; within-site variance was greater than between-site variance. For example, the WD and EO sites were not statistically different but the difference in means was 698 Bq/m^2 (2423 vs 1725 Bq/m^2 respectively). This is a large difference and estimates of erosion based on these means would also be very different. Assuming a value for an eroded soil at both sites of 1000 Bq/m^2 and similar values for bulk density and horizon thickness, the calculated erosion at the WD site would be 67 kg/m^2 whereas the erosion at the EO site would be calculated to be 47 kg/m^2. This was a 30% difference for two sites which are only 12 km apart.

^{137}Cs Activity in Bulk Density Samples

Differences in the between-slope position means for non-cultivated sites may be explained in part by differences in Ah thickness. The bulk density samples were considered to be representative of the 0-7.6 cm layer at all sites. The bulk of the ^{137}Cs is believed to be in the upper Ah horizon due to the lack of downward mobility of ^{137}Cs. If

^{137}Cs is concentrated in the upper few cm of all Ah horizons, then different sampling thicknesses at different sites may introduce a different dilution factor for each horizon. In order to take this potential effect into account, the samples taken for bulk density were analyzed for ^{137}Cs. The mean ^{137}Cs activities were much lower than those of the sampled horizons, ranging from 600 to 1080 Bq/m^2 for all slope positions and from 203 to 1848 Bq/m^2 for 3 slope positions (Table 3.4).

The variance for the bulk density samples is in the same order of magnitude as that for the sampled horizons: the CV's ranged from 26% to 110% for all slope positions and from 24% to 44% for the top three slope positions. However, there was considerable variability in the activity of ^{137}Cs at each site and between all sites for sampled horizons and in the upper 7.6 cm. Thus the means for bulk density are not considered to be representative of the background activity of ^{137}Cs because only the top 7.6 cm were sampled but the variance associated about the mean confirms the interpretation of sampled horizon data. This finding is consistent with the analysis of the sampled horizons and suggests that the vertical distribution of ^{137}Cs is not as important in explaining the overall variability as is the horizontal distribution.

Relationship of ^{137}Cs to Landscape and Soil Properties

The variance in ^{137}Cs activity in non-cultivated sites might be explained by a large number of factors which include: slope position, slope aspect, slope gradient, infiltration capacity, nature and location of vegetative cover (as it affects precipitation patterns), soil properties that influence the retention of ^{137}Cs in the soil and the nature and intensity of precipitation events. A subset of these factors was determined for each of the sampling sites, slope positions and samples. The measured slope and soil properties were correlated with the activity of ^{137}Cs measured in Bq/kg (Table 3.5). Correlation coefficients of less than 0.4 were deleted from the table. None of the correlation coefficients were high, suggesting that individual relationships are not strong.

Slope properties (gradient, position, aspect) would be expected to be important controlling factors in ^{137}Cs distribution because slope properties are linked closely to hydrologic and pedogenic processes. For some sites, downslope redistribution of ^{137}Cs appears to have occurred; yet for other sites the concentration was higher in upper slope positions compared to lower slope positions. The variance of ^{137}Cs activity at each slope position (Table 3.2) indicated that the variability at each slope position was as great as the variance between-slope positions. Slopes of small gradient would be expected to be characterized by higher activities of ^{137}Cs compared to those of higher gradient, yet the relatively flat HN site had a lower activity compared to the steeper WD site.

The correlation of slope gradient to ^{137}Cs activity for all sites was quite poor; although better (>0.4) correlation coefficients are noted for two sites, the signs of these coefficients are opposite. The distance from the top of the slope correlated with ^{137}Cs activity at six of the seven sites but again the sign of the correlation was mixed, suggesting different physical relationships at different sites. At those sites with positive correlations, there was a positive downslope trend of ^{137}Cs activity which suggests hydrologic redistribution of the radionuclide. Three sites were characterized by this response and three were not. Therefore, it would appear that slope properties are not a controlling influence on ^{137}Cs distribution at all sites and that different physical processes are operational at different sites.

Thickness of the A horizon and bulk density were negatively correlated with ^{137}Cs activity with thin horizons and horizons with low bulk density containing more of the radionuclide than other horizons. Percent organic carbon correlated with ^{137}Cs activity for most sites and generally had high coefficients. Moderately high correlations with nitrogen were probably related to the carbon-nitrogen cycle and not to ^{137}Cs interacting with nitrogen. Intermediate correlations with sodium and potassium were probably related to the similar ionic properties of these Group 1A elements and not to some physical interaction between elements. Total exchange capacity was also positively correlated with ^{137}Cs, with

the single exception of the KZ site. Correlations with particle size fractions occurred at four sites for sand content and for three sites for silt content and at one site for clay content. The sign of the correlation coefficients was mixed for particle size fraction. The lack of positive correlation with clay content is contrary to the published literature (Tamura 1964) which indicated that ^{137}Cs is associated with the clay fraction and in particular with weathered micaceous clays which are common in most Alberta soils.

Stepwise regression analysis was employed to evaluate the relationship of soil and landscape properties to the activity of ^{137}Cs (Table 3.6). No single set of variables was found to explain the variability of the activity of ^{137}Cs at all sites. At the EO site, 71% of the relationship was explained by a combination of gradient and Ah thickness while percent carbon and bulk density explained an additional 11% of the relationship. Percent carbon contributed from 1% to 92% of the relationship and was included in the regression for all sites with the exception of the MC site. For four sites (YS, WD, HN and HL), percent carbon explained from 26% to 92% of the relationship of ^{137}Cs to soil properties. The thickness of the Ah horizon explained from 25% to 42% of the variance in the relationship at the EO, KZ and WD sites.

These statistical relationships may or may not be causally related. Even though percent carbon is useful for explaining most of the variance in ^{137}Cs activity at four sites, there may be no causative effect of percent carbon on ^{137}Cs. Maulé and Dudas (1989) found that the organic-rich silt to sand sized separates of a sample with high ^{137}Cs activity contained a significant proportion of ^{137}Cs. If ^{137}Cs is linked in some way to the carbon-nitrogen cycle, then knowledge of this cycling may be useful in understanding the variability of ^{137}Cs on the landscape.

Influence of Base Level ^{137}Cs Activity on Soil Erosion Estimates

Any uncertainty associated with the base level of ^{137}Cs translates into uncertainty about the associated measure of soil erosion. The amount of erosion for the eroded knolls

at the WD site, as estimated using the methodology of de Jong et al. (1982) and the Monte Carlo simulation developed herein, was calculated to be 110 kg/m^2 with a ^{137}Cs base level of 2422 Bq/m^2 and value of 619 Bq/m^2 for the eroded knolls. The simulated base value of ^{137}Cs was 2460 Bq/m^2 with a standard deviation of 723 Bq/m^2. The simulated base level values were normally distributed based on histograms and values for skewness and kurtosis (data not presented). The small differences between the simulated base level and the measured base level are related to distribution characteristics. The measured base values of ^{137}Cs approximate the normal distribution whereas the simulated random numbers are normally distributed by definition.

The simulated mean soil erosion for the eroded knolls was 107 kg/m^2 with a standard deviation of 15 kg/m^2. The standard deviation is equivalent to 1.3 cm of soil loss compared to the mean soil loss of 8.9 cm. The coefficient of variation of soil loss was 14% compared to 30% for ^{137}Cs activity. There is a 67% probability that the rate of soil erosion falls in the range of 92 kg/m^2 and 122 kg/m^2. Therefore, reported values of soil erosion using ^{137}Cs should not be taken as fixed values but should have an estimate of error or an estimate of probability associated with them.

The simulated data for erosion were somewhat skewed due to the method of calculation of soil loss. The soil loss calculation dampened the effects of the variability of the base level of ^{137}Cs activity and also tended to skew the distribution of the soil loss estimate. The damping effect of the calculation reduced, to a degree, the influence of the high variability of the base level of measured ^{137}Cs activity on erosion estimates. The variance associated with the base level of ^{137}Cs cannot be used directly to calculate the variance in the estimate of soil erosion because of the damping effect of the calculation. Rather, some simulation technique which incorporates the soil loss calculation must be used.

There was no apparent statistical difference between the non-cultivated and the cultivated sampled populations (Fig. 3.1) at the other sites, therefore the simulation was not

run for those sites because the populations were not statistically different. Estimates of soil erosion could not be substantiated. The lack of statistical difference between non-cultivated and cultivated sampled populations was due to the within-site variance of the base level of ^{137}Cs. This indicates that the use of background activities of ^{137}Cs compared to activities in cultivated fields has limitations for estimating low rates of soil erosion. However, at a site where erosion is extreme, the technique provides a estimate of the total soil loss as in the case of the eroded knolls of the WD site.

CONCLUSIONS

The base level of ^{137}Cs for seven non-cultivated sites within a 4000 km^2 area in east-central Alberta was highly variable. Its variability was high at each slope position sampled, between slope positions and among the sites sampled. Differences among sites might be explained in terms of rainfall patterns and slope properties. The spatial variability of ^{137}Cs on non-cultivated landscapes is not easily explained by soil and landscape properties but may be related to the soil carbon-nitrogen cycle and surface water hydrology.

The high variability between cultivated and non-cultivated samples at six of the sites was sufficient to make estimates of erosion difficult because there was no statistical difference between the non-cultivated and the cultivated sampled populations. The amount of soil erosion for the WD site was estimated to be 107 kg/m^2 with a standard deviation of approximately 14%. The effect of high variance of base level ^{137}Cs is damped by the soil loss calculation; thus, the variance of ^{137}Cs on non-cultivated landscapes cannot be used directly to calculate the error associated with soil loss estimates. The ^{137}Cs technique, as used here, appears to be valid in situations where the amount of erosion is extreme but estimates of erosion in locations of low to moderate erosion are difficult due to the high variability of the base level of ^{137}Cs activity.

Estimates of soil erosion using the ^{137}Cs technique have an inherent variability associated with them based on the variability of base level ^{137}Cs. Studies aimed at

measuring soil erosion with ^{137}Cs should take into account the variability of the radionuclide on non-cultivated landscapes and quantify the effect of this variability on estimates of soil erosion. Estimates of soil erosion based on the ^{137}Cs technique should be accompanied by an estimate of the variability based on the base level of ^{137}Cs variance.

Table 3.1 Landform descriptions for sampled sites.

Site	
EO	Orthic Black Chernozemic soils on hummocky morainal landforms with slopes ranging from 16 to 30%. The soils have developed on fine loamy till parent material and are members of the Elnora or Beaverhills series.
HL	Eluviated and Orthic Eutric Brunisols on hummocky glaciofluvial landforms with slopes ranging from 10 to 15%. The soils have developed on coarse textured glaciofluvial parent materials and are members of the Nicot series.
HN	Black Solodized Solonetz on undulating morainal landforms with slopes ranging from 1 to 3%. The soils have developed on fine loamy till parent material and are members of the Killam series.
KZ	Orthic Gray Luvisol on undulating and hummocky morainal landforms with slopes ranging from 5 to 30%. The soils have developed on dense fine loamy till parent material and are members of the Cooking Lake series.
MC	Orthic Dark Gray Chernozemic rolling residual landforms with slopes ranging from 5 to 30%. The soils have developed on fine loamy parent material derived from local bedrock and are members of the Brosseau series.
WD	Orthic Black Chernozemic on hummocky morainal landforms with slopes ranging from 5 to 30%. The soils have developed on fine loamy till parent material and are members of the Elnora and Beaverhills series.
YS	Orthic Dark Gray Chernozemic on hummocky morainal landforms with slopes ranging from 3 to 30%. The soils have developed on fine loamy till and are members of the Falun series.

Table 3.2 ^{137}Cs activity in non-cultivated landscapes for each site and slope position.

Site	Slope Position	Slope Gradient (%)	A Horizon Thickness (m)	Bulk Density (Mg/m^3)	Mean ^{137}Cs (Bq/m^2)	Standard Deviation (Bq/m^2)	CV (%)
EO	CREST	2	0.06	1.07	1900	307	16
EO	UPPER	18	0.07	1.00*	1293	312	24
EO	MID	19	0.15	1.00	1982	1028	52
EO	LOWER	18	0.20	0.57*	1064	320	30
EO	TOE	2	0.30	0.57	2142	606	28
EO	DEPRN	1	0.30	0.57*	3583	1909	53
KZ	CREST	1	0.09	1.63	1039	190	18
KZ	UPPER	20	0.07	1.52*	832	178	21
KZ	MID	22	0.07	1.52	1017	65	6
KZ	LOWER	20	0.09	1.59	1603	244	15
KZ	TOE	11	0.15	1.45	607	359	59
KZ	DEPRN	1	0.15	1.67	428		
HL	CREST	2	0.15	1.49	1044	89	9
HL	UPPER	6	0.22	1.49*	1741	466	27
HL	MID	10	0.21	1.34	1631	504	31
HL	LOWER	16	0.35	1.25	1390	270	19
HL	TOE	6	0.69	1.21	1696	160	9
HL	DEPRN	1	0.56	0.83	1377	890	64
HN	CREST	1	0.14	1.04	1906	246	13
HN	UPPER	2	0.13	1.04*	1780	501	28
HN	MID	3	0.12	0.97	2316	1674	72
HN	LOWER	3	0.08	0.97*	2311	1131	49
HN	TOE	2	0.09	0.97*	1256	1490	118
HN	DEPRN	1	0.13	0.58	3098	1456	47
MC	CREST	2	0.11	0.68	2223	1401	63
MC	UPPER	15	0.18	0.74	2001	864	43
MC	MID	26	0.21	0.72	2069	925	45
MC	LOWER	20	0.26	0.82	1820	564	31
MC	TOE	16	0.18	0.60	1079	359	33
MC	DEPRN	4	0.28	0.43	827	399	48
WD	CREST	4	0.18	1.17	2713	713	26
WD	UPPER	15	0.09	1.01	2224	352	16
WD	MID	18	0.16	1.01	2002	355	18
WD	LOWER	16	0.35	1.04	4956	1706	34
YS	CREST	3	0.18	0.94	449	172	38
YS	UPPER	12	0.12	1.15	640	292	46
YS	MID	16	0.21	0.76	2228	1333	60
YS	LOWER	13	0.27	1.13	6409	1648	25
YS	TOE	3	0.31	0.77	1851	1555	84
YS	DEPRN	1	0.07	0.91	10444	7792	74

* Estimate based on value for adjacent location.

Table 3.3 Statistics for the activity of ^{137}Cs on non-cultivated landscapes for each site based on six and three slope positions.

Site	N	Mean (Bq/m²)	Standard Deviation (Bq/m²)	CV (%)	N	Mean (Bq/m²)	Standard Deviation (Bq/m²)	CV (%)	Direc. of Change	Change % of mean	CV Change (%)
	All Slope Positions				3 Slope Positions *						
EO	18	1990	1143	57	9	1725	647	37	-	13.3	-20
HL	20	1596	589	37	11	1624	648	39	+	1.8	+2
HN	18	2112	1172	55	9	2001	915	45	-	5.3	-10
WD	18	2845	1374	48	15	2423	853	35	-	14.8	-7
YS	22	3804	4265	112	11	1870	1628	87	-	50.8	-25
KZ	17	950	418	44	9	963	166	17	+	1.4	-27
MC	18	1604	864	53	9	1966	969	49	+	22.6	-4

N = number of samples.
CV = coefficient of variation.
* crest, upper and mid slope positions.

Table 3.4 Statistics for the activity of ^{137}Cs on non-cultivated landscapes for each site based on six and three slope positions in bulk density samples.

Site	N	Mean (Bq/m²)	Standard Deviation (Bq/m²)	CV (%)	N	Mean (Bq/m²)	Standard Deviation (Bq/m²)	CV (%)	Direc. of Change	Change % of mean	CV Change (%)
	All Slope Positions				3 Slope Positions *						
EO	9	600	658	110	6	203	50	24	-	66.2	-86
HL	8	595	152	26	5	555	138	25	-	6.7	-1
HN	9	1007	364	36	6	982	302	31	-	2.5	-5
WD	5	1080	728	67	3	1346	588	44	+	24.6	-23
YS	12	778	356	46	8	1848	304	36	+	137.5	-10

N = number of samples.
CV = coefficient of variation.
* crest, upper and mid slope positions.

Table 3.5 Pearson correlation coefficients of ^{137}Cs (Bq/m^2) activity on slope and soil properties.

Slope / Soil Property	Site							
	BO	HL	HN	KZ	MC	WD	YS	All
Slope gradient	-0.62	-*	-	0.62	-	-	-	-0.17
Dist. from top of slope	-0.47	0.58	0.50	-0.57	-0.60	-	0.70	0.17
Ah thickness	-	0.56	-	-0.80	-0.51	-	-0.44	-0.14
Bulk density	-	-0.60	-0.70	-	-	0.40	-	-0.29
pH	-	0.45	-	-0.60	-	-	-0.50	-0.25
N	-	-	0.61	0.56	-	0.71	0.80	0.45
% Carbon	0.44	0.68	0.78	0.60	-	0.78	0.83	0.41
Na	0.52	0.67	-	0.44	-	0.61	-	0.02
K	0.68	-	0.58	-	0.51	0.72	-	0.42
Ca	-	0.68	0.49	-0.79	-	-	0.70	0.36
Mg	0.46	0.72	-	0.42	-	-	0.41	0.16
Total Exchange Capacity	-	0.69	0.67	-0.59	-	-	0.80	0.46
Sand	-0.51	-0.64	-	0.71	0.41	-	-	-0.12
Silt	0.56	0.69		-	-	-	0.46	0.36
Clay	-	-	-	-0.69	-	-	-	-0.23

* - = values deleted when $r < 0.40$.

Table 3.6 Parameters of regression analysis of ^{137}Cs (Bq/m^2) on soil and landscape variables.

Variable	Partial R^2	Model R^2	F	Prob>F
Site: EO				
Gradient	0.46	0.46	11.2	0.0051
Ah thickness	0.25	0.71	10.6	0.0067
% Carbon	0.08	0.80	4.5	0.0552
Bulk Density	0.03	0.83	2.1	0.1690
Site: HL				
% Carbon	0.47	0.47	13.6	0.0022
Site: HN				
% Carbon	0.60	0.60	24.3	0.0001
Site: KZ				
Ah thickness	0.39	0.39	6.4	0.0296
Total Exch. Capacity	0.41	0.81	20.0	0.0015
% Carbon	0.01	0.82	0.4	0.5429
Bulk Density	0.01	0.83	0.6	0.4487
Gradient	0.02	0.86	1.0	0.3379
Site: MC				
Dist. from top of slope	0.36	0.36	9.2	0.0077
Total Exch. Capacity	0.11	0.47	3.1	0.0958
Site: WD				
Ah thickness	0.42	0.42	5.0	0.0587
Bulk Density	0.26	0.69	5.2	0.0623
% Carbon	0.26	0.95	31.6	0.0025
Total Exch. Capacity	0.01	0.97	3.5	0.1328
Site: YS				
% Carbon	0.92	0.92	191.5	0.0001
Ah thickness	0.02	0.95	8.9	0.0091
Dist. from top of slope	0.01	0.96	3.0	0.1030
Gradient	0.01	0.96	0.3	0.5460

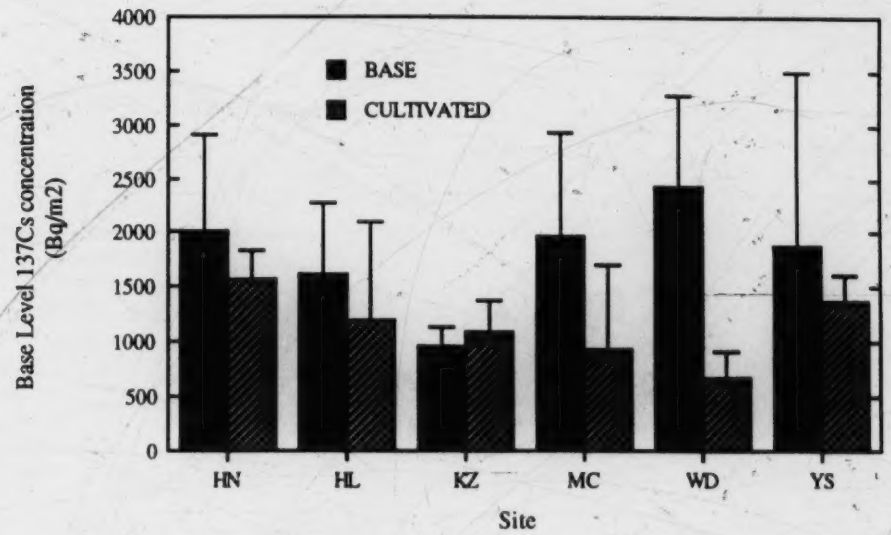

Figure 3.1 Base level ^{137}Cs activity and standard deviation of Ah (Ap) horizon in comparison to cultivated activities for three slope positions (crest, upper and mid).

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CHAPTER 4

RILL AND INTERRILL EROSION OF CHERNOZEMIC SOILS IN EAST-CENTRAL ALBERTA

INTRODUCTION

Water erosion resulting from springmelt runoff and intense summer rainfall is the cause of considerable soil erosion in east-central Alberta. Chanasyk and Woytowich (1986) identified the period of springmelt to be a time of high susceptibility to water erosion in the Peace River region. This period is characterized by frozen ground that is only slightly pervious, allowing some infiltration of melting snow, resulting in runoff and an increased potential for soil erosion as the ground thaws during melting. Springmelt occurs annually throughout most of Alberta and may be the cause of significant water erosion (Chanasyk and Woytowich 1986). Intense summer rainfall is common throughout most of Alberta and is another cause of significant water erosion. Storms are usually short in duration and generally affect only a small proportion (km^2) of the landscape.

Water erosion is the result of three processes: interrill, rill and gully erosion. Interrill erosion is the movement of water and soil over the land surface and does not generally result in observable features as do rill and gully erosion. Interrill erosion occurs on a scale of 0.05 to 10 m in length. Rill erosion is caused by concentrated flow of water over the landscape and results in the formation of small channels called rills. Rills may be 10 to 40 cm deep, 0.2 to 3.0 m wide and up to several 100 m in length. On agricultural landscapes, rill erosion is often masked because conventional cultivation techniques eradicate the channels. Rills grade into gullies. Gullies can be ten's of meters in depth and width, several 100 m long and often form an impediment to cultivation. Gully erosion is not common in east-central Alberta.

Deposition is a process that accompanies erosion, but deposition is often ignored in upland soil erosion studies. Deposition also occurs at a variety of scales. On a geological time scale, all deposition occurs in the lakes and oceans. There are numerous locations on cultivated fields where deposition occurs as a result of rill and interrill erosion. These locations of deposition impede the movement of eroded soil from the upland into rivers and streams and should be taken into consideration when measuring soil loss.

APPROACHES TO MEASURING OR ESTIMATING SOIL EROSION

A combination of techniques have been employed to measure or estimate soil erosion on cultivated fields. Plot studies are by far the most common technique for measuring erosion. In Alberta, Toogood (1963) and Chanasyk and Woytowich (1986) used Wischmeier-type plots to estimate water erosion in the Edmonton and Peace River regions, respectively. van Vliet et al. (1983) also used plots in the Peace River region for estimating erosion. Luk (1975) used a modified plot design to evaluate soil erosion in the Bow River basin. Plot studies are excellent for comparing treatments such as cropping practice on soil loss but do not separate the contributions of the processes of rill and interrill erosion to total soil yield. In addition, plot studies do not give any indication of the fate of the eroded material.

The Universal Soil Loss Equation (USLE) was developed from plot studies throughout the United States. The USLE is the most commonly used estimator of upland soil erosion. It is based on the evaluation of six factors (Rainfall, soil erodibility K, Slope gradient, slope Length, Cropping practice, and erosion control Practice). However, the applicability of the USLE is limited in Alberta due to frozen ground conditions characteristic of springmelt in Western Canada. Tajek et al. (1985) proposed a modified R factor for inclusion in the USLE to take these factors into account. The modified R factor was based the calculation of Zachar (1983) and uses snow depth, snow density and the rate

of snowmelt at the time of thaw. The modified R factor assumes uniform distribution and melting of snow on the landscape.

In the USLE, the average annual soil loss from a unit area of land is calculated using regression analysis of many years of plot data. The calculation of average annual soil loss lumps the processes of rill and interrill erosion. The plots used to develop the USLE were located on uniformly sloping portions of the landscape and thus, did not include convexity or concavity in land surface form. The results of USLE calculations are therefore only applicable to a portion of the landscape, but not to the total landscape. The equation has also been applied at a drainage basin scale. Such applications generally ignore the range of slope positions (upper, mid and lower) and the presence of intermediate depositional locations. Soil loss is generally considered to be uniform within the basin and soil deposition cannot be calculated.

The Water Erosion Prediction Project (WEPP) aims to use a physically based continuous simulation model based on modern hydrologic and erosion science (Lane and Nearing 1989) to replace the statistically based USLE. The model is reported to account for soil loss and soil deposition on hillslopes and the project includes the future development of watershed and grid versions. The model includes ten components which include: weather, snowmelt and frozen soil, infiltration, surface runoff, soil, water balance and percolation, plant growth, hydraulics and overland flow, irrigation and erosion. The WEPP model is implemented as a hillslope profile erosion model and as such does not consider complex surface form although it is designed for temporal and spatial variability in soil properties, cropping patterns, crop growth and hydrology. WEPP is designed to separate rill and interrill erosion using a steady-state sediment continuity equation (Foster et al. 1989).

Morgan (1979) reported that 98% of measured erosion was the result of rill flow and that only 2% was attributable to rain splash and interrill flow. The study was conducted on a one centimeter width of an 11% slope. Morgan believed that an

understanding of the relative contributions of rill and interrill erosion was needed to estimate or measure soil erosion.

Few studies to date have separated the relative contributions of rill and interrill erosion on agricultural landscapes. Roels and Jonker (1983) used erosion pans to measure rill and interrill erosion on rangelands in France. They treated the amount of erosion on the landscape as a population of values that they sampled using erosion pans. Soil erosion was analyzed in terms of probability distribution functions; which were found to be skewed or bimodal in nature. They concluded that the amount of soil erosion on the rangeland was highly variable and that the most effective sampling procedure was to measure total rill erosion and to sample the interrill subpopulation.

In order to evaluate soil erosion on a landscape basis, the dominant processes must be identified and measured. Understanding the contribution of each process to soil loss or soil gain is vital to modeling soil-erosion. This study was initiated to determine the relative amounts of rill and interrill erosion and soil deposition on agricultural landscapes in east-central Alberta and to evaluate their spatial and temporal variability.

MATERIALS AND METHODS

Interrill Erosion

Soil erosion pans, similar to those described by Roels and Jonker (1983), were used to measure interrill erosion in two summerfallow fields at two research sites in east-central Alberta.

The sites selected were within WD and YS sites described in Chapter 3 (Table 3.1) and were characterized by fine loamy Orthic Black Chernozemic soils on till parent material. These sites were selected because they were summerfallowed and because of similar soils and topography. The WD site was characterized by hummocky topography with slope gradients ranging from 4 to 9% and was eroded as evidenced by the presence of knolls with lime carbonate at the soil surface. The YS site was characterized by hummocky

topography with slope gradients ranging from 4 to 9% superimposed on a regional westerly slope of 3 to 4%.

The sites were monitored regularly throughout the summer and spring seasons (1986 to 1988) in response to summer rainfall events and during the springmelt period. Springmelt monitoring was daily whereas erosion from summer rainfall was monitored bi-weekly or in response to major storm systems moving through the region.

Pan locations at each site took into account the range of slope positions, slope gradients and furrow direction in each of the sites under investigation between 1986 and 1988. The pans were installed 'en echelon' (Fig. 4.1), in groups of three or four as described by Morgan (1979) and Roels and Jonker (1983). Three to five groups of three pans each were installed on one to three slopes at each site during the late spring to early summer and monitored until fall. Three to five groups of three pans each were added at each of the sites in the fall prior to freeze up in order to collect springmelt runoff on two to three more slopes. At each site, 33 to 36 pans were installed and monitored in 11 to 12 slope positions at each site during springmelt. Pan locations were selected on each slope to characterize upper and mid slope positions. In cases where slope length was greater than 30 m, pans were installed in lower slope positions.

Pan design was a modified Gerlach trough, 50 cm in width at the front, 39 cm in length and 5 cm in height (Fig. 4.2). Two modifications were employed to allow installation and removal of the pans during the study, as necessitated by cropping practice and season. The first was related to pan installation. Whereas Roels and Jonker (1983) used concrete to create a base for pan installation, the pans in this study were installed directly on the soil surface and secured in place with plastic tent pegs. The second modification related to collection devices. Two plastic pails were used to collect sediment and runoff water. An outer pail with a v-notch was used to collect overflow from an inner 10 l pail. The 10 l pail served as a primary collection unit which could be removed and capped easily.

During springmelt, the 10 l collection pails were replaced with new pails as they became full and were either capped or added to 20 l pails that were later capped. Field notes were taken to record the approximate volume of water and sediment collected and the time of day when it was collected. Field notes were also maintained on the distribution and approximate density of snow cover during springmelt. Quantitative data on the distribution and density of snow cover could not be collected given the short duration of the melt period and the difficulty of registering density, depth and location data with the Digital Elevation Model (DEM). All snow cover data in the text are qualitative.

At the conclusion of each spring melt or summer rainfall erosion event, the soil remaining on the pan was removed and bagged separately but included in the calculation of total interrill erosion. The water and sediment collected during the melt were separated by allowing the sediment to settle in the pails for several weeks. The pails were weighed and the water was then decanted leaving a slurry of soil and water which was subsequently oven dried. The mass of soil was determined directly and the volume of runoff water was calculated as the difference between the mass of the pail and soil and the mass of the pail, soil and water. Sediment yield and runoff volume were totaled for each of the three pans at each location for each event and then averaged for each pan location. The average value of the three pans was taken to represent the sediment yield and runoff volume for the slope position under consideration.

Rill Erosion

A rill meter, as described by McCool et al. (1981), was used to measure the amount of rill erosion. The rill meter consists of a rigid exterior frame with internal, vertically mobile rods. The exterior frame is positioned on the soil surface across a rill and the rods are lowered to obtain a cross-sectional measure of the rill. Several observations along a rill were used to integrate the measurements of cross-sectional area into estimates of volume of soil removed. Each rill was divided into characteristic sections based on the width and

depth of the rill. Rills were subdivided into main system segments and subsystem segments where main system segments were the widest, deepest and best defined parts of the rill pattern. Subsystem segments were smaller by an order of magnitude in width and depth compared to the main system segments but were longer than main system segments.

The surface area from which soil removal occurred within a segment was calculated by multiplying the width of rill segment by its length and summing for all segments. The volume of each rill segment was calculated by multiplying the cross-sectional area for each segment by the length of the segment and summing for all segments. The total rill surface area and rill volume were calculated by adding surface area and volume estimates of all rill segments (main system and subsystem rills), respectively.

Deposition

The YS basin was selected for a detailed study of erosion and deposition. Locations of rill erosion (rill patterns) and locations of soil deposition, as a result of rill erosion, were identified in the field and mapped using a Zeiss total survey station in relation to fixed survey markers. The areal extent of deposition for the YS site was determined by surveying the perimeter of the depositional location and calculating its area. The area subject to interrill erosion was calculated as the difference between the total cultivated area in the basin and the sum of the rill and depositional areas.

One location in the YS basin, characterized by deposition, was sampled in 5 cm vertical increments to determine the depth of the radioisotope ^{137}Cs to be used to determine the base of the Ap horizon at the time fallout started (de Jong et al. 1982). The total amount of soil deposition was calculated as the depth of depositional material since 1955 (de Jong et al. 1982), when ^{137}Cs is reported to have started to fall on the landscape, times the total area of deposition times an assumed bulk density of 1.20 Mg m^{-3}.

Meteorological Measurements

Meteorological data were recorded at each study site, on an hourly basis during spring and summer using an Omnidata Easylogger. Sensors included: a Li-Cor pyranometer, a R. M. Young wind monitor, a Fenwal thermistor for air temperature, a Sierra Misco tipping bucket rain gauge and a Vaisala humidity sensor. Wind speed and direction and air temperature were monitored on an hourly basis during the fall and winter months. Notes were maintained on the distribution and depth of snow during the winter months at each of the sites where pans were installed but are not reported herein. The meteorological data were used in explaining the forces that caused measured erosion during the study period. Precipitation and temperature data were obtained from the Atmospheric Environment Service (AES) climate records for the Vegreville CDA station and were compared to the study sites' precipitation and temperature data for the study period (1986 to 1988).

RESULTS AND DISCUSSION

Erosion From Springmelt Events

Winter precipitation (November through February) and temperatures in (1986) were typical whereas the following two years were drier and warmer than the 30 year normal (LTN), 1951-1980. Recorded winter precipitation in 1985/86 at the Vegreville CDA station was 7 mm greater than the LTN of 62 mm (Table 4.1). In both subsequent years of the study, there was less winter precipitation (53.7 and 30.8 mm respectively) compared to the LTN. The average air temperature recorded during the first winter of the study was close to the LTN of -12.9°C (Table 4.2). The following two years were warmer than normal, with average winter temperatures of -8.7° and -7.9°C respectively.

The melt period in 1986 was the warmest and longest of the study period (Table 4.3). The average daily temperature was 3.8°C over a period of 6 days in 1986. The average daily temperatures during springmelt in 1987 and 1988 were 2.5° and 2.0°C

respectively over melt periods of 4 and 5 days respectively. The melt period of the second year was characterized by more solar radiation on average (417 W/m^2) than those of the first or third year with 270 and 138 W/m^2 respectively. The melt period occurred in mid to late February in 1986 and 1988 whereas melting occurred in late March in 1987. Springmelt in 1986 was the longest, warmest and had the highest overwinter precipitation.

The erosion pan data from three springmelt events at the two sites (Tables 4.4 to 4.7) are representative of a range of values for interrill erosion on the slopes in each field. The data are presented as total soil collected (g) (pan and bucket) and total runoff (l), averaged over the pans installed at each slope location.

The distribution of soil loss in east-central Alberta was skewed (data not presented) markedly towards low values by the relatively few slope positions with high amounts of interrill erosion. Very little soil was collected by the majority of pans whereas considerable soil was collected in a small number of pans. Roels and Jonker (1983) similarly reported that the distribution of soil loss samples departed from the normal distribution. Since the sampled population deviates considerably from the normal distribution, parametric statistics (mean and standard deviation) are not appropriate for describing the sampled population.

The greatest soil losses were from the steepest slopes and with furrow directions perpendicular (leading into pan) to the pan. The high amounts of interrill erosion were due to the formation of small (1 to 3 cm wide) channels in tillage furrows that produced 20 l of runoff in approximately 15 minutes during the warmest part of the day. These small channels were subsequently filled in during the latter stages of melt and no surface evidence of their existence remained. These channels on the NPAS slope were 5 to 12 m in length and with a width of 2 cm and a depth of 1 cm would contribute 2.8 kg of soil loss. This is within the range of amounts of soil collected on slopes with the highest amounts of erosion. The length of these small channels varied in time and for each pan. The maximum length of contribution to erosion pans only of 12 m whereas the minimum length of contribution was on the order of centimeters.

Morgan (1979) stated in order to express pan data in units of area that the distance to the top of the slope times the width of the pan was the catchment area. Field observations indicated that this is an unrealistic approach to estimating soil loss because the area of contribution varies depending on snow cover, direction of furrow and time of day. It proved difficult, in most circumstances during the melt, to keep accurate estimates of the length factor; therefore, no attempt was made to express the data on an area basis. Roels and Jonker (1983) expressed pan data in units of mass per unit width of slope.

The pans that collected the least amounts of soil were either located on gentle slopes or on steeper slopes where the pan installation was parallel or oblique to the direction of cultivation. The influence of tillage on interrill erosion can be seen by comparing Slope 6 with Slope 3 for 1987 at the WD site. The gradients and snow cover on these two slopes were similar but the furrow direction on Slope 3 was parallel to the pan and considerably less soil was collected.

The winters of 1987 and 1988 had less snow than normal (Table 4.1) and were milder than the LTN (Table 4.2). In 1987, the amounts of interrill erosion were influenced by snow cover. Slopes 1 and 6 at the WD site were similar with respect to gradient and furrow direction but had marked differences in snow cover and density. Slope 1 was covered with fresh snow whereas Slope 6 was covered with accumulations of wind deposited snow from the winter. The snow on Slope 6 was characterized by layers of dense granular snow interspersed with thin layers of ice. Slope 6 was subject to high amounts of interrill erosion whereas Slope 1 had low amounts of interrill erosion.

Springmelt rill erosion was measured in 1986 and 1988 at the YS and in 1987 at the WD sites (Tables 4.8 and 4.9). Rill erosion at the YS site was characterized by two major rill patterns in a cultivated area of 4.7 ha. One occurred in the southern part of the basin (SBM) and the other in the northern part of the basin (NBM). Each of these main channels was joined by a series of smaller subsystems of rills (SBS and NBS). Considerably more erosion occurred in the north portion of the basin primarily because of a larger contribution

from subsystem rills compared to the south part of the basin. Measured springmelt rill erosion at the YS site in 1986 was 22.8 Mg compared to 4.2 Mg at the WD basin in 1987. Rill systems were less defined and smaller in the WD basin in 1987 (Table 4.9) compared to the rill systems in the YS basin.

Considerably more springmelt rill erosion occurred in 1986 than in 1987 or 1988, likely due to the snow cover which was observed to be denser and more uniform in 1986 than in subsequent years (data not presented). Snow cover was more or less evenly distributed over the landscape in 1988 but was reasonably fresh at the time of melt and therefore less dense than would be expected based on the 1986 melt. Masterton et al. (1976) reported the mean snow depth for the portion of Alberta under study to be on the order of 25 to 38 cm of snow on February 28. In 1986 and 1988, this thickness of snow was present at both sites but the snow was fresh and less dense in 1988 than in 1986. In 1987 the snow pack was highly variable across the fields being monitored having been redistributed by wind across the fields.

The soil to water ratio from the pans was highly variable over the period 1986 to 1988 (Tables 4.4 to 4.7). In 1986 and 1987 the ratio varied from 1.1 to 85.2 g l^{-1} and the averages for the YS and WD basins for both years respectively were 10.8 and 9.0 g l^{-1}. The soil to water ratios measured in 1988 were substantially greater than in 1986 and 1987 with a range of values from 65.2 to 821.3 g l^{-1} and basin averages of 244.0 and 114.8 g l^{-1} for the YS and WD basins respectively. Substantially less runoff water was collected in the pans in 1988 (0.5 and 4.6 l on average for the YS and WD sites) compared to 1987 (46 l on average at the WD site) and 1986 (49 l on average for the YS site). Even though there was less runoff in 1988 compared to 1987 and 1986, the sediment in the runoff was more concentrated in 1988. In essence, greater concentrations of soil moved over short distances in small quantities of water in 1988 compared to 1986 and 1987 when greater amounts of water with smaller amounts of soil moved over greater distances.

The distribution and density of snow pack and the intensity and duration of the springmelt are believed to be largely responsible for the variability of soil loss (rill and interrill) during springmelt. Other factors which influenced soil loss were slope position, slope gradient and tillage pattern. Infiltration rate was concluded not to be a factor in erosion measurements because in all cases the soil at the surface was frozen during springmelt.

Soil Erosion From Summer Rainfall

Summer precipitation (April through August) in 1986 was exactly the LTN for the region, whereas 1987 was marked by lower precipitation and 1988 by higher (22%) than normal precipitation (Table 4.1). Most of the extra precipitation fell in the months of June and August coinciding with observed rill erosion for the region of study.

Trace amounts of soil were collected from the pans in 1986 and 1987. These minute quantities of soil appeared to be the result of splash erosion as the soil was plastered to the walls and bottoms of the pans with little evidence of flow present. Further, very little water was collected in the buckets, indicating that the soil collected in the troughs was not washed in by surface flow.

Rill erosion was observed throughout the area of study in June and August of 1988 due to heavy summer rainfall. A short duration, high intensity rain storm (Fig. 4.3) in August of 1988 resulted in 83.9 Mg of soil loss (Table 4.8) and the formation of a network of rills in both the north and south portions of the YS basin. Tillage erosion between 1986 and 1988 filled and smoothed the 1986 rill network. The main segments of the rill networks were in the same locations as the rill networks from the 1986 springmelt. These pathways were in locations of the landscape that collected water from surrounding areas but were able to transmit that water downslope. These pathways were convex in across-slope direction and had positive downslope gradient.

Soil Deposition

Soil deposition was noted at both sites in all three years and most of the material eroded by rill or interrill erosion was observed to be deposited within the study sites. Interrill erosion resulted in soil deposition either in erosion pans or on the slope upon which the interrill erosion was initiated. Even in areas of high interrill erosion, deposition was observed to occur on the same slope as erosion. Interrill erosion occurred on a scale of 0.5 to 12 m. Deposition from rill erosion occurred at much greater distances from the source of erosion compared with interrill erosion. Areas of deposition were 20 to 250 m from the source of soil loss.

Locations of deposition from rill erosion in the YS basin were characterized by 70 to 80 cm depositional sequences. With depth, these sequences consisted of buried Ap horizons separated by layers of sand and cross bedded sand and organic matter. The radioisotope ^{137}Cs was present to a depth of 35 cm suggesting that the base of the Ap horizon was at approximately 35 cm in 1955. If the Ap were 15 cm thick in 1955, as it is today, then approximately 20 cm of soil have been deposited over the last 23 years. With an estimated area of deposition of 1824 m^2 (Table 4.10), 20 cm of deposition would require 365 m^3 or 438 Mg of soil loss from the upper portions of the basin. Such loss would require 19 erosion events of the magnitude of the 1986 spring melt or 5 events of the magnitude of the August 1988 rainfall event over the 23 years since the start of fallout.

Combined Effects of Rill, Interrill Erosion and Deposition

Rill erosion is responsible for the detachment and transport of more soil over longer distances than interrill erosion (Table 4.8). The high amounts of erosion resulting from rilling occur only on a small (1.2 - 3.5%) (Table 4.10) percentage of the landscape. High amounts of interrill erosion are also characteristic of only a small portion of the landscape as indicated by the small number of pans with high collections of soil. Interrill erosion was characteristic of the majority (> 90%) of the land surface in each of the basins as indicated

by the large number of pans with small amounts of soil collected. Interrill erosion was responsible for the movement of soil over short distances whereas rill erosion is responsible for the movement of more soil over longer distances (20 - 250 m) on these landscapes. If locations of rill erosion could be identified quantitatively on the landscape, locations most susceptible to erosion could be identified and mapped. Likewise, locations of deposition could be mapped if there were characteristic features. For example, locations of deposition in the field appear to be flat or concave whereas locations of rill erosion appear to be concave with positive downslope gradient. Locations of high interrill erosion might be delineated through gradient and curvature information.

The pattern of rilling at the YS site followed the same pathways in the basin during the springmelt of 1986 and the summer rainfall of 1988. Between 1986 and 1988, the 1986 rill network had been filled with soil and smoothed over by conventional tillage operations (tillage erosion) but in 1988 approximately 110 m^3 of soil was removed from a surface area of 1627 m^2 due to rill erosion. Cultivation and interrill processes recharge the rill networks for subsequent removal of soil downslope. The soil eroded in 1988 was subsequently deposited in the locations of deposition noted in 1986. The locations of deposition now appear full of soil. Surfaces of locations of deposition are level with the field boundary and as such, runoff into an adjacent slough at the bottom of the landscape will occur. It will take many erosion events of the magnitude measured for this slough to fill and for runoff eventually to flow out to the next stage in the hydrologic cycle which is a nearby creek.

The WD basin was also subject to severe erosion in the summer of 1988. Two storms caused measurable interrill erosion and one caused measurable rill erosion. Unlike the YS basin, rill formation occurred on different slopes than those in 1987. This might be attributed to the slope characteristics in the WD basin. The WD basin is on hummocky topography, characterized by short steep slopes. The YS basin, which is also on hummocky topography, has a regional slope upon which the hummocks are superimposed

thus providing some avenue for rill formation over a greater distance. The WD basin does not have a regional slope and therefore runoff is limited primarily to the short steep slopes. It would be more difficult to predict rill formation based on slope characteristics in the WD basin than in the YS basin.

CONCLUSIONS

The highest amounts of interrill erosion were characterized by the formation of small channels which were filled with soil in the latter stages of the melt thus leaving no trace of their presence. This phenomenon occurred on a single slope in the YS basin in 1986 and on two slopes in the WD basin in 1987. The highest amounts of interrill erosion were measured on the steepest slope with cultivation furrows perpendicular to the maximum gradient.

Rill erosion was concentrated in a very small portion of each basin but when rill erosion occurred it resulted in much greater soil loss than interrill erosion. In addition, soil eroded by rill erosion was transported considerably greater distances than soil eroded by interrill processes. The maximum length of contribution to erosion pans was approximately of 12 m whereas the measured rill length ranged from 140 to 1791 m. The amount of soil collected in erosion pans in upper, mid and lower slope positions was not cumulative and in most cases the lower slope pans collected less soil than those on the upper slope. This is consistent with the results of Roels (1985) and means that increased slope length does not always result in increased soil movement.

Cultivation filled and smoothed the rill pattern, effectively providing more soil to be eroded during the next event. The term tillage erosion was used to describe this phenomenon because tillage implements were responsible for the detachment and transport of soil.. The area of the field affected by tillage erosion was not measured. The overall effect of tillage erosion was to increase the area of soil loss for the whole field and increase the likely hood of continued rill erosion.

Soil deposition resulting from rill erosion occurred at both sites but only on small portions of the landscape. The combination of erosion pans and the rill meter provided valuable measurements on the occurrence and severity of water erosion processes in the YS basin. Erosion pans and rill meter methods would work well in a wide variety of settings but are limited because many years of data collection would be required to obtain the full range of erosion events.

Table 4.1 Precipitation (mm) for the period 1985 to 1988 and Long Term Normal precipitation for the Vegreville CDA station.

Month	Measured Precipitation	LTN* Precipitation
	1985 - 1986	
November	15.4	14.6
December	34.9	16.9
January	12.0	16.6
February	6.8	13.9
Winter total	69.1	62.0
April	27.1	14.0
May	45.5	35.8
June	45.7	73.5
July	130.2	74.5
August	23.8	74.5
Spring - Summer total	272.3	272.3
	1986 - 1987	
November	20.9	14.6
December	9.2	16.9
January	7.6	16.6
February	16.0	13.9
Winter total	53.7	62.0
April	21.6	14.0
May	35.6	35.8
June	28.9	73.5
July	66.6	74.5
August	68.5	74.5
Spring - Summer total	221.2	272.3
	1987 - 1988	
November	1.4	14.6
December	8.3	16.9
January	5.7	16.6
February	15.4	13.9
Winter total	30.8	62.0
April	18.3	14.0
May	18.4	35.8
June	139.3	73.5
July	42.2	74.5
August	114.2	74.5
Spring - Summer total	332.6	272.3

* Long Term Normal (1951 to 1980)

Table 4.2 Winter temperatures (°C) for the period 1985 to 1988 and Long Term Normal temperatures for the Vegreville CDA station.

Month	Average Measured Monthly Temperature	LTN* Temperature
	1985 - 1986	
November	-15.8	-6.1
December	-9.3	-14.0
January	-9.3	-18.1
February	-15.9	-13.4
Winter period	-12.6	-12.9
	1986 - 1987	
November	-10.2	-6.1
December	-8.2	-14.0
January	-9.1	-18.1
February	-7.4	-13.4
Winter period	-8.7	-12.9
	1987 - 1988	
November	-0.6	-6.1
December	-7.4	-14.0
January	-14.4	-18.1
February	-9.3	-13.4
Winter period	-7.9	-12.9

* Long Term Normal (1951 to 1980)

Table 4.3 Characterization of meteorological conditions during springmelt.

Year	Dates of Melt	Duration of Melt (days)	Average Daily Temperature (°C)	Average Hourly Solar Radiation (W/m^2)	Average Daily Wind Speed (km/hr)
1986	Feb. 24 to Mar. 1	6	3.8	270	-
1987	Mar. 31 to Apr. 3	4	2.5	417	14
1988	Feb. 17 to Feb. 21	5	2.0	138	19

Table 4.4 Measured springmelt interrill erosion at the YS site, Feb. 24 - March 1, 1986.

Slope Location	Slope Aspect	Slope Position	Slope Gradient (%)	Distance from top of Slope (m)	Furrow Direction*	Soil Collected (g)	Runoff Collected (l)	Ratio Soil / Water (g/l)
NPAS	North	Upper	11	12	perpendicular	2505	125	20.1
NPAS	North	Mid	11	24	perpendicular	1651	103	16.0
NPAS	North	Lower	11	36	perpendicular	1230	98	12.6
Average for whole slope **						1795	109	16.5
NMET	North	Upper	10	12	parallel	108	10	10.8
NMET	North	Lower	10	24	parallel	63	12	5.3
Average for whole slope						86	11	7.8
WMET	West	Upper	9	12	oblique	140	15	9.3
WMET	West	Lower	9	24	oblique	201	69	2.9
Average for whole slope						170	42	4.0
WHOU	West	Upper	9	12	parallel	38	13	2.9
WHOU	West	Lower	9	24	parallel	63	53	1.2
Average for whole slope						50	33	1.5
Average for whole basin ***						530	49	10.8

* Relative to the long axis of the pan.
** Average of all pans on the slope.
*** Average of all pans in the basin.

Table 4.5 Measured springmelt interrill erosion at the WD site, March 31 - April 3, 1987.

Slope Location	Slope Aspect	Slope Position	Slope Gradient (%)	Distance from top of Slope (m)	Furrow Direction*	Soil Collected (g)	Runoff Collected (l)	Ratio Soil / Water (g/l)
1	West	Upper	15	14	perpendicular	80	44	1.8
1	West	Lower	10	24	perpendicular	42	40	1.1
Average for whole slope**						61	42	1.5
2	north	upper	18	15	parallel	67	4	16.8
2	north	mid	13	19	parallel	45	5	9.0
2	north	lower	13	30	parallel	48	3	16.0
Average for whole slope						53	4	13.3
3	N.East	Upper	20	17	parallel	68	12	5.7
3	N.East	Lower	16	31	parallel	307	58	5.3
3	N.East	Lower	14	30	parallel	201	247	0.8
Average for whole slope						192	106	1.8
4	N.West	Mid	5	15	perpendicular	33	34	1.0
5	S.West	Upper	12	3	parallel	67	2	33.5
6	East	Mid	17	12	perpendicular	3080	159	19.4
6	East	Lower	11	24	perpendicular	1705	20	85.2
Average for whole slope						2392	90	26.6
7	East	Mid	17	12	oblique	105	44	2.4
Average for whole basin***						415	46	9.0

* Relative to slope direction.
** Average of all pans on the slope.
*** Average of all pans in the basin.

Table 4.6 Measured springmelt interrill erosion at the YS site, Feb. 17 - Feb. 21, 1988.

Slope Location	Slope Aspect	Slope Position	Slope Gradient (%)	Distance from top of Slope (m)	Furrow Direction*	Soil Collected (g)	Runoff Collected (l)	Ratio Soil /water (g/l)
75	East	Upper	5	16	perpendicular	95	0.7	135.7
75	East	Mid	5	24	perpendicular	84	0.3	280.0
75	East	Lower	3	22	perpendicular	59	0.2	295.0
Average for whole slope**						80	0.4	200.0
78	East	Upper	8	24	parallel	197	0.4	492.5
78	East	Lower	7	34	parallel	65	1.0	65.0
Average for whole slope						131	0.7	187.1
80	S.East	Upper	7	22	perpendicular	75	0.5	150.0
80	S.East	Lower	7	31	perpendicular	130	0.8	162.5
Average for whole slope						103	0.7	147.1
82	S.East	Upper	7	16	parallel	69	0.4	172.5
82	S.East	Lower	7	31	parallel	97	0.3	323.3
Average for whole slope						83	0.4	207.5
84	North	Upper	5	15	parallel	181	0.3	603.0
84	North	Lower	5	26	parallel	241	0.3	803.0
Average for whole slope						211	0.3	703.0
Average for whole basin***						122	0.5	244.0

* Relative to slope direction.
** Average of all pans on the slope.
*** Average of all pans in the basin.

Table 4.7 Measured springmelt interrill erosion at the WD site, Feb. 17 - Feb. 21, 1988.

Slope Location	Slope Aspect	Slope Position	Slope Gradient (%)	Distance from top of Slope (m)	Furrow Direction*	Soil Collected (g)	Runoff Collected (l)	Ratio Soil / Water (g/l)
100	West	Upper	15	16	Oblique	462	0.8	577.5
100	West	Lower	15	30	Oblique	421	4.1	102.7
Average for whole slope**						442	2.5	176.8
103	East	Mid	9	12	perpendicular	657	0.8	821.3
103	East	Lower	9	18	perpendicular	699	2.2	317.7
Average for whole slope						678	1.5	452.0
104	N.West	Upper	5	17	parallel	92	0.2	460.0
104	N.West	Lower	5	29	parallel	194	2.1	92.4
Average for whole slope						143	1.2	119.2
106	West	Upper	7	15	perpendicular	909	11.0	82.6
106	West	Lower	7	26	perpendicular	787	15.0	52.5
Average for whole slope						848	13.0	65.2
Average for whole basin***						528	4.6	114.8

* Relative to slope direction.
** Average of all pans on the slope.
*** Average of all pans in the basin.

Table 4.8 Measured rill erosion for the YS site.

Rill Code	Rill Length (m)	Rill Surface Area (m^2)*	Rill Volume (m^3)**	Mass of Soil lost (Mg)***	Soil Loss (kg/m^2)
1986 springmelt					
NBM	111	131	10	12.0	92
NBS	342	191	8	9.6	50
SBM	161	164	8	9.6	59
SBS	285	51	2	2.4	47
TOTAL	899	537	28	22.8	
1988 August rainfall					
NBM	384	463	32	38.4	83
NBS	421	392	26	31.2	80
SBM	248	461	31	11.5	25
SBS	738	311	21	2.8	9
TOTAL	1791	1627	110	83.9	

* length times width for all rill segments.
** length times cross-sectional area summed for all rill segments.
*** based on a bulk density of 1.20 Mg m^{-3}.

Table 4.9 Measured springmelt rill erosion for the WD site 1987.

Rill Code	Rill Length (m)	Rill Surface Area (m^2)*	Rill Volume (m^3)**	Mass of Soil lost (Mg)***	Soil loss (kg/m^2)
EAST	80	20	1	1.2	60
WEST	19	19	1	1.2	63
GATE	41	17	2	1.8	106
TOTAL	140	55	4	4.2	

* length times width for all rill segments.
** length times cross-sectional area summed for all rill segments.
*** based on a bulk density of 1.20 Mg m^{-3}.

Table 4.10 Relative areas of contribution to rill and interrill erosion and deposition.

Site	Year	Total Area of Basin (m^2)	Area of Interrill Erosion (m^2)	Percent of Total Area	Area of Rill Erosion (m^2)	Percent of Total Area	Area of Deposition (m^2)	Percent of Total Area (%)
YS	1986	47056	44695	95	537	1.2	1824	3.8
YS	1988	47056	43605	92.7	1627	3.5	1824	3.8

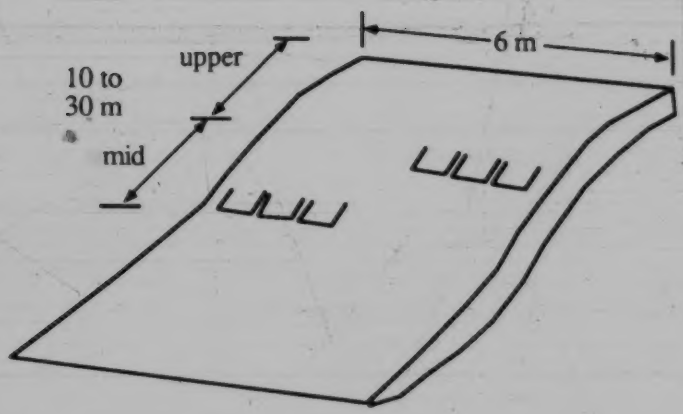

Figure 4.1 Layout of pans on slope surface.

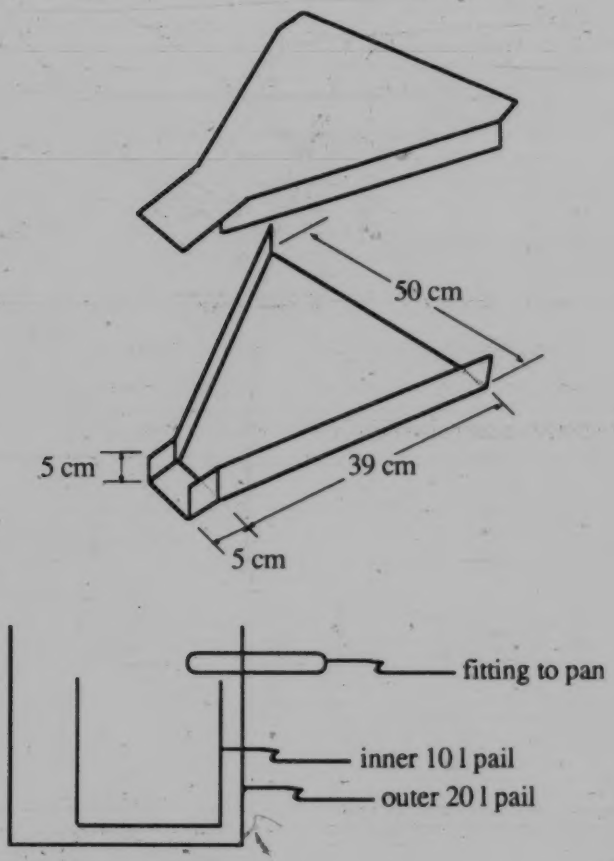

Figure 4.2 Soil erosion pan design.

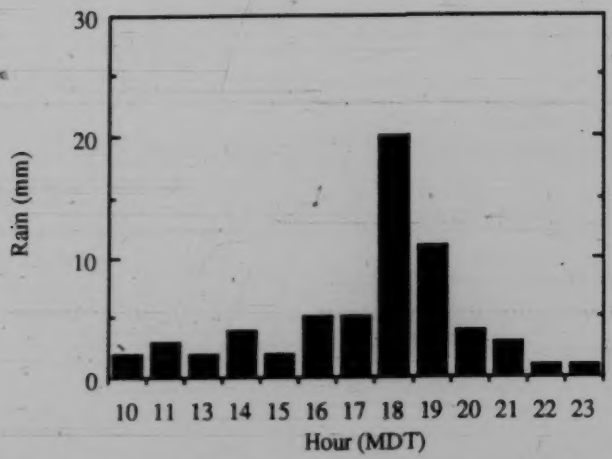

Figure 4.3 Hourly rainfall pattern during the erosive storm of Aug. 20, 1988 (YS site).

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CHAPTER 5

RILL EROSION, INTERRILL EROSION AND DEPOSITION ON AN AGRICULTURAL FIELD IN RELATION TO SURFACE FORM

INTRODUCTION

Soil erosion is highly variable in space and in time. Water erosion can result from short duration, high intensity events which are distributed non-uniformly over time and over the landscape. Rill erosion is responsible for the removal of more soil, but affects a smaller portion of the landscape compared to interrill erosion (Chapter 4). Soil deposition also occurs because of erosion processes but is rarely included in soil loss calculations. The combined effects of these three soil erosion processes (rill, interrill and deposition) must be measured when describing and modeling water erosion, when making regional estimates of water erosion or when making farm-scale conservation plans.

Campbell (1985) discussed the partial area concept of runoff production and its application to sediment source areas. The partial area concept suggests that the area of a basin producing runoff and sediment is usually much less than the total area. Measurements of rill and interrill erosion (Chapter 4) indicated that, for one small basin in east-central Alberta, very small portions of the landscape accounted for the greatest soil loss. Equivalently small portions of the landscape were found to account for the greatest soil gain. These measurements support the partial area concept of sediment delivery to areas of deposition.

Khanbilvardi et al. (1983) and Khanbilvardi and Rogowski (1984) developed a model characterizing upland erosion based on the Universal Soil Loss Equation (USLE) and transport/detachment functions. They divided the landscape into rill and interrill erosion zones on 100 m grid and used detachment and transport functions to model soil

erosion and deposition. Rill patterns were generated using slope steepness and direction. Their computer-generated rill patterns corresponded well with existing drainage patterns in the basin. This approach to modeling water erosion takes into account spatial variability of erosion processes. The determination of which parts of the landscape are subject to rill erosion, interrill erosion and deposition when complex surface form is recognized is probably more complicated than suggested by Khanbilvardi and Rogowski (1984). Furthermore, the temporal variability of erosive meteorological events, runoff and water erosion was not considered in their model.

The earth's surface is traditionally described using topographic maps. More recently, Digital Elevation Models (DEM's) have been employed to describe the surface of the earth in mathematical terms and used to infer the occurrence of surface processes such as soil erosion (Pennock and de Jong 1987); to quantify surface form characteristics (Lanyon and Hall 1983, Franklin 1987, Pennock et al. 1987, Pennock and de Jong 1987); hydrological modeling (Heerdegen and Beran 1982, Zevenbergen and Thorne 1987); to enhance Landsat classification (Niemann 1988) and to quantify landslide-terrain types (Pike 1988). The conceptual approach taken by these authors was that land surface form and land surface processes were linked to each other and that relationships between surface form and surface process could be identified.

A DEM is a matrix of elevation data that describes the surface of the geographic area. Digital Terrain Modeling (DTM) techniques are designed to describe quantitatively the earth surface using mathematical techniques to analyze DEM's. Elevation data are represented in an array or finite element matrix and calculations of the first derivative (slope gradient) and second derivative (slope curvature) can be performed using finite difference techniques (Eyton Pers. Comm.) or using the first and second derivatives of a polynomial equation (Young and Evans 1978, Heerdegen and Beran 1982, Pennock et al. 1987, Zevenbergen and Thorne 1987).

DEM's can also be used to relate water movement to surficial features or phenomenon including: flowpath (Eyton Pers. Comm.); catchment and detachment areas (Martz and de Jong 1985) and slope form classifications (Pennock and de Jong 1987). Flowpath values are computed for each grid element in an elevation model as the number of times a roving 3 x 3 matrix passes through a given grid element in a DEM from upslope. Catchment area, used by Martz and de Jong 1985, is a measure of the area upslope of each grid element whereas dispersal area is a measure of water shedding capacity. Pennock and de Jong (1987) described seven landform elements related to the flow of water on the landscape and defined these landform elements quantitatively using slope gradient, plan slope curvature and profile slope curvature. Each of the six classes were defined by converging or diverging water flow. These measures were related to water flow on the landscape, and thus, they can potentially be used to model water erosion and water movement on the land surface.

Pennock and de Jong (1987) discussed the influence of slope curvature and gradient on soil erosion and deposition in a hummocky moraine landscape. They used the concentration of the radionuclide ^{137}Cs to estimate soil erosion and the depth of ^{137}Cs in soil profiles to measure deposition. The landscape was classified into one of seven slope classes based on downslope and across-slope curvature using a 10 m elevation grid. The classification system was largely based on the predicted flow of water over the landscape and traditional measures of slope position. They found distinctive differences among most landform elements in terms of soil loss or gain. Differences in soil loss or gain were explained by the predicted behavior of water flow on the landscape.

Rill and interrill erosion, as well as deposition, were measured in a small basin in east-central Alberta using in situ measurements of erosion processes with erosion pans and a rill meter (Chapter 4). Soil loss and gain were observed to be confined to very small portions of the landscape which had distinctive surface form characteristics. For example, locations of deposition were concave or flat whereas locations of rill erosion were also

concave but were sloping downwards towards the locations of deposition and were contiguous with similar landscape elements. Locations of interrill erosion were characterized by convex or planar slope elements. In order to model water erosion on a landscape basis, the slope elements characterized by different erosion processes were identified and mapped so that their response to simulated erosion events could be evaluated.

The purpose of this study was to measure rill and interrill erosion and deposition on the landscape as a function of surface form characterized by digital terrain derivatives for a research site in east-central Alberta.

MATERIALS AND METHODS

The experimental design was established to compare land surface form with erosion processes using digital terrain derivatives, statistical analyses and mapping procedures (Fig. 5.1). All of the processing of the DEM to produce digital terrain derivatives and flowpath counts was performed using computer programs developed by Eyton (Pers. Comm.). A 3 x 3 matrix was used to calculate a value for the center point of the matrix and replace original DEM elevation data with the calculated value. The 3 x 3 matrix is the smallest matrix that will allow for calculation of the digital terrain derivatives of interest.

Digital Elevation Models can be developed in a variety of ways using either topographic maps, land survey information or from aerial photographs using photogrammetry. For the purposes of this study, a digital elevation model was developed for the YS site (Chapter 2) using photogrammetric techniques. The DEM consisted of a square matrix of elevation data for the site taken on a 4 x 4 m interval. Locations in the matrix of elevation data that were not cultivated, e.g., a slough in the northwest corner and the farm yard in the north east corner, were excluded from all analyses. These locations are identified on maps of the basin included herein.

The YS site was photographed, using standard aerial cameras, at a scale of 1:3,500. Ground control was established by placing large targets on the land surface at five locations

within the site. At the center of each target, a steel stake was driven into the ground and these stakes were surveyed with respect to one another to establish actual surface elevation. Point measures of elevation were taken on a 4 m grid with a vertical resolution of 10 cm using a Zeiss stereo analytic plotter (Energy and Natural Resources). The survey data from the target installation were used to correct the elevation data for the tilt and yaw of the aircraft in order to represent the land surface correctly. The final elevation data were stored electronically by the Zeiss stereo analytic plotter and transferred via magnetic tape to the University of Alberta's computing facilities for analysis. The surface of the basin was plotted using custom software (plotz) developed by Eyton (Pers. Comm) and standard plotting facilities at the University of Alberta. Analysis of the DEM was performed with software provided by Eyton (Pers. Comm) and with software developed by the author.

Slope gradient and curvature are the first and second derivatives of the elevation matrix respectively. The finite difference technique described by Eyton (Pers. Comm.) was used to calculate slope gradient, downslope curvature, across-slope curvature and flowpath using the elevation data for the site. This method was chosen because it does not presuppose the nature of the surface under study (e.g., by assuming a polynomial function to describe the surface). Since the finite difference technique does not fit a specified polynomial equation to elevation values for a particular neighborhood, the actual elevation data for each grid element are used to calculate first and second derivatives of the elevation matrix. The technique employed by Eyton produces signed and scaled values for downslope and across-slope measures of curvature using a linear interpolation technique as opposed to solving polynomial equations for the second derivative as employed by others (Evans 1972; Pennock et al. 1987). The downslope curvature is calculated along the axis of maximum slope and the across-slope curvature is calculated on an axis perpendicular to the downslope curvatures. The direction of curvature need not conform to the x and y axes of the neighborhood matrix used (Niemann 1988).

Flowpath counts were accumulated for each grid element in the DEM by following the path of steepest descent from the top of the basin to the bottom of the basin or until level ground is reached. A 3 x 3 grid element matrix was used to identify the path of steepest descent by moving the 3 x 3 matrix to the next lowest grid element in the model. The flowpath count for each grid element is incremented by one as the roving 3 x 3 matrix passes through. When the bottom of the basin is reached, the 3 x 3 matrix is returned to the grid element at the the top of the basin and one element laterally to where it started to resume the search for the path of steepest descent. High values of flowpath are used to designate water drainage network of a given basin because the path of steepest drainage follows descent paths from the top to the bottom of the basin. Low flowpath values designate locations of low water flow because the path of steepest descent does not move through these grid elements as often as high flowpath grid element.

Rill and interrill erosion were measured in the YS research basin using soil erosion pans and a rill meter from springmelt to the end of the growing season from 1986 to 1988 (Chapter 4). The location of rills and locations of deposition were surveyed using land survey techniques with a Zeiss total survey station shortly after the 1988 summer erosion event when the field was in summerfallow. These locations were transformed into the coordinate system of the DEM so that the locations of soil erosion and deposition could be analyzed in terms of surface form measurements. Values for slope gradient, downslope and across-slope curvature and flowpath were extracted from the digital terrain derivatives for grid elements characterized by rill erosion and deposition. The remainder of the grid elements in the DEM were assumed to be characterized by interrill erosion based on erosion pan data and field observation.

The number of grid elements defined as interrill was much greater than the number of either the rill and depositional grid elements (2935 interrill grid elements compared to 213 rill and depositional grid elements). Comparing all of the interrill grid elements in the model with the rill and depositional grid elements would bias the results given the large

number of interrill grid elements. To facilitate statistical analysis of these three categories of grid elements, the interrill population was randomly sampled to produce subsets of DTM records that were not statistically different for the variables of slope gradient, downslope and across-slope curvature and flowpath. The interrill population was sampled randomly five times to produce five data sets of 100 grid elements each and five data sets of 150 grid elements each. The subsets of the interrill population were compared for statistical differences using analysis of variance. The five subsets of interrill grid elements with 100 members each were statistically different for a subset of the digital terrain derivatives. The five subsets of interrill grid elements with 150 members each were not statistically different with respect to the digital terrain derivatives, and a sixth subset of the interrill population was then generated using the same random selection technique. The sixth set of 150 interrill grid elements was used for statistical comparison with the 99 rill and 114 depositional grid elements.

The SAS procedure Proc Univariate was used to develop descriptive statistics to test for normality and to develop frequency distributions for the three classes of grid elements (depositional, interrill and rill). Stem and leaf analysis, box plots and histograms were also produced for each of the three classes of grid elements using Proc Univariate in order to study the nature and distribution of the data prior to further statistical analyses.

Analysis of variance was performed with Proc Anova to compare the means of slope gradient, downslope and across-slope curvature and flowpath for the three classifications of erosional processes. The means for each classification were compared using Duncans Multiple Range Test to determine which classifications were different or the same for specific digital terrain derivatives.

Discriminant analysis of the three classes of grid elements was performed with Proc Discrim. Discriminant analysis is a statistical technique that is used to develop classification functions for classified data based on numeric variables. In this case, the numeric variables are the digital terrain derivatives and the classes are the rill, depositional

and interrill classifications based on measured erosion. All observations are used to develop the classification function. The function is then used to reclassify each of the observations in the data set and provide a measure of prior probability of membership to a particular classification. Observations not classified into their original classification are treated as miss-classified. This analysis provides a tool to compare groups of classified data with one another, develop a function for classification and to classify other records with the same numeric variables into groups of classified data.

Discriminant analysis also provides a listing of all of the records used in the analysis, a classification based on the disciminant classifier, the original classification and the probability of membership in each classification. These data and Proc Univariate were used to develop descriptive statistics, for the properly classified and the miss-classified grid elements (depositional, interrill and rill) in order to compare and contrast these groups of data.

All of the rill, interrill and depositional grid elements were plotted in the basin using software developed by the author and standard plotting facilities of the Alberta Research Council. Properly classified and miss-classified grid elements (as per discriminant analysis) were plotted in the basin to compare and contrast their locations in relation to the locations of originally classified grid elements.

RESULTS AND DISCUSSION

The YS site is a cultivated field characterized by fine loamy Orthic Black Chernozemic soils on a hummocky morainal landscape (Chapter 3). The basin, within which this site is situated, was located on a regional west facing slope and was characterized by north and south facing slopes superimposed on the regional slope (Fig. 5.2). The basin is bounded on the east by a field boundary adjacent to a highway and on the west by a pasture and a slough. The basin is bounded on the south by a topographic high and on the north by a field boundary and farm yard. The total elevation difference

from top to bottom of the basin is approximately 12 m over a distance of 224 m and the average gradient of the basin is 3°. The site is managed using conventional farming methods for the region with a crop - crop - fallow rotation.

Surface Form Characteristics of Rill, Depositional and Interrill Grid Elements

The locations of rill, depositional and interrill grid elements selected for statistical analysis were mapped on the basin (Fig. 5.3). The surveyed rill grid elements form two distinct lineations in the basin. The surveyed depositional grid elements are clustered in two distinct locations at the base of the lineations of rill grid elements whereas the interrill grid elements that were selected for analysis are scattered randomly throughout the basin.

The means for gradient, across-slope curvature, downslope curvature and flowpath were calculated for rill, interrill and depositional grid elements (Table 5.1). Locations of interrill erosion had steeper gradients (4.2°) compared to rill and depositional grid elements (3.7° and 1.4° respectively). Interrill grid elements had higher across-slope curvature (0.024°/m) compared to rill and depositional grid elements (-0.337°/m and -0.069°/m respectively). Interrill grid elements had higher downslope curvature (0.058°/m) compared to rill and depositional grid elements (-0.085°/m and -0.075°/m respectively). The interrill grid elements had the lowest flowpath numbers (12) compared to rill and depositional grid elements (66 and 157 respectively). The depositional grid elements had the greatest flowpath counts (157) and the lowest values for gradient (1.4°) of the three classifications. Rill grid elements had the greatest values for across-slope curvature (-0.337°/m), the lowest values for downslope curvature (-0.085°/m) and intermediate values for gradient (3.7°) compared to the interrill and depositional grid elements.

Depositional grid elements were located on flat or concave portions of the landscape with high flowpath values. Rill grid elements were characterized by the strongest negative across-slope curvature of all three classifications, positive downslope gradient and negative downslope curvature. Grid elements defined as interrill had the strongest slope gradient

and the lowest flowpath values of the three classifications and were also characterized by positive downslope and across-slope curvature. Rill erosion occurred on slope elements with concave across-slope curvature, positive downslope gradient while soil deposition occurred on concave or flat slope elements. Interrill erosion occurred on the steepest slope gradients of the three classifications but had the lowest flowpath values and were the only group with positive across-slope and downslope curvatures. The analysis of rill grid elements does not demonstrate that these grid elements are contiguous with similar grid elements, all of which accumulate runoff water (concave across-slope curvature) and that pass that runoff water downslope (positive downslope gradient) towards locations of deposition.

Values of skewness and kurtosis indicated normal distributions for all variables except flowpath for rill and depositional grid elements. Distributions for rill and depositional grid elements were skewed by a few very high values of flowpath as indicated by normal probability plots (data not presented). The occurrence of a small number of grid elements with very high flowpath numbers was related to the occurrence of rill and depositional grid elements in the lower portion of the basin towards which many of the upper grid elements slope.

The three classifications of grid elements were statistically different for slope gradient, across-slope curvature and flowpath ($P \leq 0.05$) (Table 5.1). Downslope curvature values for rill and depositional grid elements were statistically different from those for interrill grid elements. Interrill grid elements were characterized by positive downslope curvature whereas rill and depositional grid elements were characterized by negative downslope curvature. The rill and depositional grid elements were not statistically different for downslope curvature, being both negative and relatively low. Each of the three classifications of grid elements was uniquely characterized by some set of terrain derivatives. Therefore, the digital terrain derivatives could be used in a discriminant analysis to quantify the relationship between surface form and erosion process.

Discriminant Analysis of Rill, Depositional and Interrill Grid Elements

Although analysis of variance indicated that the digital terrain derivatives of the three classifications of grid elements were statistically different, there is no indication of which combination of derivatives makes each group unique. Furthermore, there is no way to classify other grid elements as rill, interrill or depositional based on the results of analysis of variance.

The discriminant classifier resulting from discriminant analysis was effective in reclassifying depositional and interrill grid elements but was less effective at reclassifying rill grid elements (Table 5.2). Of the 99 rill grid elements in the basin, 52% were correctly classified by the discriminant classification function whereas 94% of the interrill grid elements and 79% of the depositional grid elements were correctly classified (Table 5.2). The majority of miss-classified rill grid elements were classified as interrill grid elements.

The miss-classified rill grid elements had similar mean gradient (3.7°) and mean flowpath values (67 compared to 65) compared to properly classified grid elements (Table 5.3). The miss-classified rill grid elements had lower mean downslope curvature values (-0.033 °/m versus to -0.135°/m) and greater across-slope curvature values (-0.184 °/m versus to -0.480°/m) compared to the properly classified grid elements (Table 5.3).

Values for gradient and flowpath were similar for correctly classified and miss-classified rill grid elements but slope curvature in both directions was lower for miss-classified grid elements compared to correctly classified grid elements. Lower values for slope curvature for miss-classified grid elements were the probable reason for miss-classification.

The locations of miss-classified rill grid elements in the basin (Fig. 5.4) were in subdued topography where rills were observed to be narrow and not well defined. The locations of correctly classified rill grid elements (Fig. 5.5) tended to map out the rill patterns in the southern portion of the basin but not in the northern portion. The majority

of miss-classified grid elements were found in the northern portion of the basin explaining the lack of pattern definition.

The low percentage of properly reclassified rill grid elements (52%) was probably related to differences in the scale of process and the scale of the elevation data. The rill erosion process occurred on a scale of 1 - 2 m in width over long distances. The original elevation data were on a 4 m grid and as such could not express subtle changes in surface form that occur at a scale of 1 - 2 m. Many of the rill grid elements have the surface form characteristics of interrill grid elements but were subject to rill erosion because a number of upslope grid elements were producing rill flow.

When a class of grid elements has similar characteristics, the percentage of properly reclassified rill grid elements is higher. The high percentage of properly reclassified depositional grid elements (79%) was related to the distinctive surface form characteristics of locations of deposition. Deposition occurred in concentrated areas of the basin (Fig 5.3) with low slopes (1.3°), high flowpath numbers (195) and concave curvature in both directions (-0.087 and -0.088 °/m downslope and across-slope respectively) (Table 5.3).

Interrill erosion occurred extensively over the basin and a random sampling of those grid elements resulted in a high percentage of properly reclassified grid elements (94%) of reclassification in the discriminant analysis. Properly classified interrill grid elements are characterized by low flowpath values (8), positive across-slope and downslope curvature (0.037 and 0.068 °/m) and with stronger gradient (4.3°) than the other two classifications (Table 5.3). Interrill grid elements were generally convex and in upper slope positions with low flowpath values.

Discriminant analysis characterized rill grid elements as having concave across-slope curvature (-0.480 °/m) and concave downslope curvature (-0.135 °/m) compared to other classes of grid elements. Rill grid elements were characterized by higher flowpath numbers (65) and lower gradient (3.7°) compared to interrill grid elements (8 and 4.3° respectively).

Depositional grid elements which were successfully reclassified by the discriminant classifier were characterized by high flowpath values and low gradient values compared to the interrill and rill grid elements. Mean values for slope curvature were similar for depositional grid elements compared to rill and interrill grid elements. Properly classified interrill grid elements were characterized by positive slope curvature in both directions, very low mean values for flowpath and higher values for slope gradient compared to the other two classes.

Locations of Surveyed Rill Grid Elements in Relation to High Flowpath Grid Elements

Rill and depositional grid elements had higher average flowpath values than interrill grid elements. It is reasonable to expect some correlation between the location of rill grid elements and grid elements with high values of flowpath because high flowpaths represent drainage networks. The drainage network of the basin as defined by flowpath is similar to the surveyed rill network (Fig. 5.6). The locations with highest flowpath numbers (greater than 50) tend to form lineations in the basin that can be used to describe drainage patterns similar to the rill patterns (Fig. 5.3). Locations with intermediate flowpath numbers (20 to 50 and 10 to 20), which occur in the lower portion of the basin, do not define lineations as do locations of higher flowpath numbers. Locations of intermediate flowpath extend into the upper portion of the basin along lineations of high flowpath. The flowpath map gives a good indication of generalized flow patterns in the basin using arbitrary class limits.

Plotting high flowpaths and the rill network revealed several differences and similarities between them (Fig. 5.7). Of the 213 grid elements with flowpath values greater than 50, only 14 (6.5%) corresponded to the locations of surveyed rill grid elements. The rill grid elements were generally very close to high flowpath grid elements indicating that flowpath calculations may be very useful for delineating generalized flow nets in the basin. The high flowpath grid elements far outnumbered the number of surveyed rill grid elements

(213 versus 99) which would result in high estimates of soil erosion if a flowpath threshold of 50 were used to delineate rill patterns.

In the absence of surveyed rill data, the locations of grid elements with high flowpath numbers could be used to approximate a drainage network, which could also be used to simulate rill erosion, if a arbitrarily chosen threshold value of 200 were used (Fig. 5.7). A threshold flowpath value of 200 resulted in a close approximation of the surveyed rill network and reduces the drainage network to 114 grid elements which is a reasonable approximation of the rill network for simulation of rill erosion.

There are several reasons for the discrepancies between the locations of high flowpath values and surveyed rill grid elements. The elevation data set from which flowpath values were calculated is on a 4 m grid with a vertical resolution of 10 cm. This is a very high resolution data set but rill erosion occurs on a smaller scale than the width of a rill, which may be less than a meter wide. Therefore, the 4 m grid element cannot be taken as truly representative of a rill.

Small nuances in field geometry (cultivation pattern, differences between actual gradient compared to calculated gradient) at the time of rilling could be responsible for differences in the location of actual rill erosion compared to the calculated locations using flowpath values. Small differences in the elevation data set compared to the real surface can also be responsible for changing the routing of the flowpath calculation. The DEM is a gridded data set located on the land surface with no reference to erosion process and as such may not represent the surface as well as it could. The actual location of a rill could have been equal distances between the elevation points in the DEM. The gradient, curvature and flowpaths calculated for those grid elements would not necessarily represent the land surface at the point of rill erosion.

Relationship Between Surface Form and Erosion Process

Depositional and interrill grid elements were easily identified in this basin using discriminant analysis, but rill grid elements were not as easily identified from the digital terrain derivatives as the depositional and interrill grid elements.

The grid elements characterized by deposition were identified by a combination of gradient, curvature and flowpath values as determined using discriminant analysis. These grid elements were plotted in two very small locations in the basin. The grid elements characterized by interrill erosion were also characterized by a combination of digital terrain derivatives and were mapped extensively through out the basin. These grid elements contributed considerably less soil over shorter distances to the soil redistribution in the basin than the rill grid elements (Chapter 4).

The rill grid elements contributed the greatest amount of soil to locations of deposition and were the grid elements with the highest amounts of soil loss. The grid elements subject to the highest amounts of erosion (rill) were the most difficult to identify from the digital terrain derivatives. However, identifying and mapping grid elements with flowpath values greater than 200 produced a runoff pattern similar in location and number of rill grid elements affected compared to measured rill patterns. The implication is that rill patterns in this basin can be identified and mapped using flowpath numbers generated from the DEM. Locations of deposition and of interrill erosion could be identified using the discriminant classifier for modeling erosion processes.

CONCLUSIONS

Most of the YS basin is subject to interrill erosion and only small portions are subject to rill erosion and deposition. Discriminant analysis provided a quantitative relationship between surface form and erosion processes; the relationship is stronger for interrill and depositional grid elements than for rill grid elements. The location and extent of rill grid elements can be approximated using flowpath values.

Locations of deposition and interrill erosion were identified with discriminant analysis using slope gradient, slope curvature and flowpath data in this basin. Locations subject to rill erosion were less easily discriminated using gradient and curvature data but grid elements with flowpath values greater than 200 delineated a flow pattern in the basin similar to the surveyed rill pattern. Digital terrain derivatives can thus be used in this basin to delineate locations of interrill erosion and deposition and flowpath numbers can be used to delineate patterns of rill erosion. The relationships between surface form and erosion processes could be used to identify and map erosion on a landscape basis.

The approach of relating erosion to surface form measurements worked well for the YS site where a detailed elevation data set was available and where detailed erosion measurements were also available. The relationships developed by discriminant analysis are not considered valid for other settings nor with other elevation data sets, particularly those with different vertical and horizontal resolution. Detailed elevation data sets are relatively easy to obtain for research sites, but obtaining the detail necessary to model erosion processes on a larger scale would be very difficult.

Table 5.1 Means of digital terrain derivatives and flowpath values for rill, interrill and depositional grid elements in the YS basin.

Location	Landscape Property	Units of Measure	N	Mean	Standard Deviation	Skewness	Kurtosis
Rill	gradient	°	99	3.7b*	1.3	0.34	0.44
Deposition			114	1.4c	0.6	0.69	0.83
Interrill			150	4.2a	1.6	0.06	-0.45
Rill	downslope curvature	°/m	99	-0.085a**	0.19	0.48	0.35
Deposition			114	-0.075a	0.17	0.03	0.51
Interrill			150	0.058b	0.31	-0.17	0.47
Rill	across-slope curvature	°/m	99	-0.337a	0.21	0.0	0.64
Deposition			114	-0.069b	0.16	0.48	0.42
Interrill			150	0.024c	0.22	-0.13	0.38
Rill	flowpath	counts***	99	66b	159	3.6	14.7
Deposition			114	157a	307	2.1	3.0
Interrill			150	12c	30	6.8	53.3

N = number of samples.
* means for each landscape property with the same letter are not statistically different.
** negative sign denotes concave curvature.
*** the flowpath calculation is in counts per grid element.

Table 5.2 Percent of grid elements classified by discriminant function into the three classifications of deposition, interrill and rill erosion.

Original* Classification	Percent of grid elements classified into:			
	Deposition	Interrill	Rill	N
Deposition	79	20	1	114
Interrill	1	94	5	150
Rill	6	42	52	99

N = number of samples.
* based on field observations, erosion pan data, rill meter data and land survey data.

Table 5.3 Means for properly classified and miss-classified grid elements from discriminant analysis.

Location	Landscape Property	Units of Measure	N (miss-classified)	Mean (miss-classified)	N (properly classified)	Mean (properly classified)
Rill	gradient	°	48	3.7	51	3.7
Deposition			24	2.0	90	1.3
Interrill			9	3.4	141	4.3
Rill	downslope curvature	°/m	48	-0.033	51	-0.135
Deposition			24	-0.044	90	-0.087
Interrill			9	-0.097	141	0.068
Rill	across-slope curvature	°/m	48	-0.184	51	-0.480
Deposition			24	-0.022	90	-0.088
Interrill			9	-0.178	141	0.037
Rill	flowpath	counts*	48	67	51	65
Deposition			24	13	90	195
Interrill			9	61	141	8

N = number of grid elements analyzed.
* the flowpath calculation is in counts per grid element.

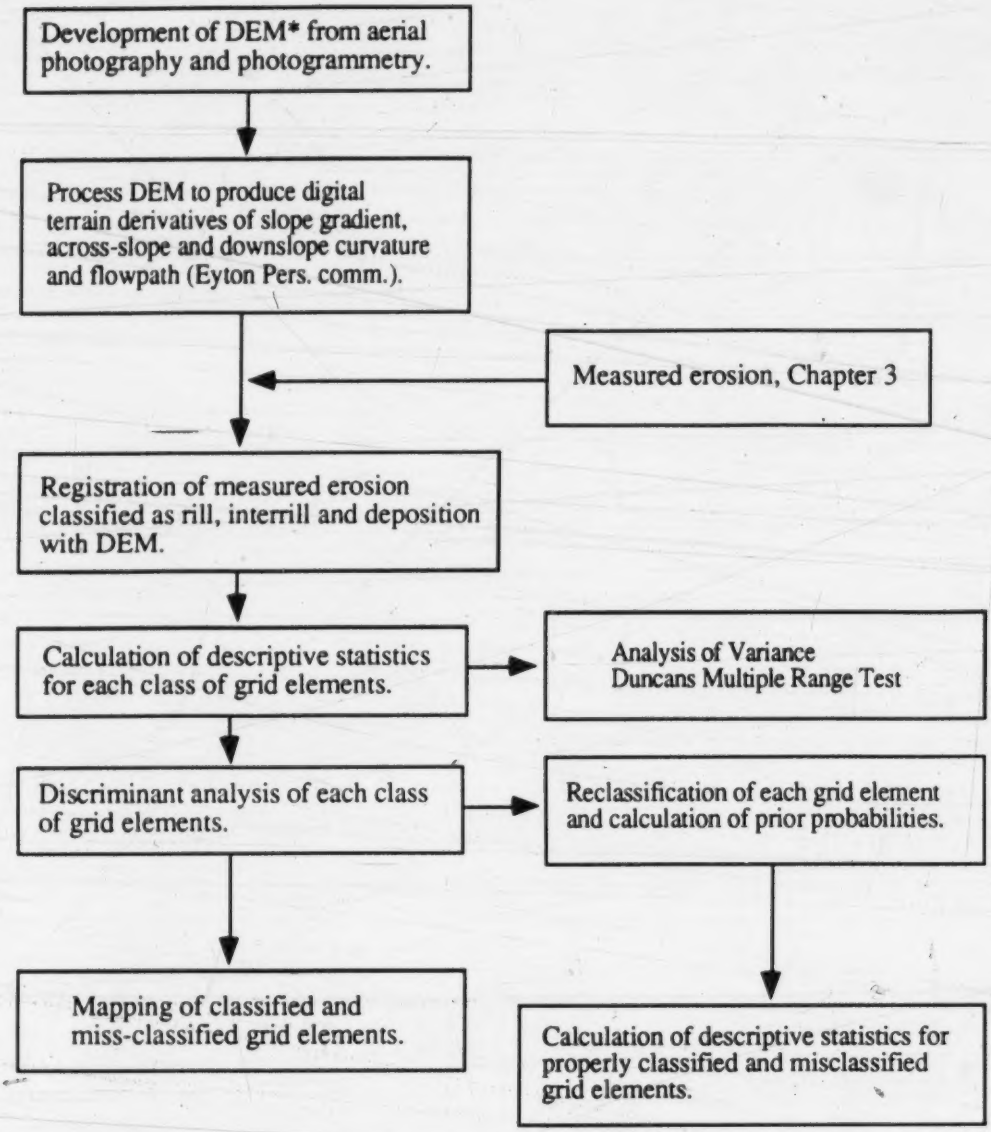
Development of DEM* from aerial photography and photogrammetry.
Process DEM to produce digital terrain derivatives of slope gradient, across-slope and downslope curvature and flowpath (Eyton Pers. comm.).
Measured erosion, Chapter 3
Registration of measured erosion classified as rill, interrill and deposition with DEM.
Calculation of descriptive statistics for each class of grid elements.
Analysis of Variance
Duncans Multiple Range Test
Discriminant analysis of each class of grid elements.
Reclassification of each grid element and calculation of prior probabilities.
Mapping of classified and miss-classified grid elements.
Calculation of descriptive statistics for properly classified and misclassified grid elements.

Figure 5.1 Flow chart of research methods and analyses (Chapter 5).

* Digital Elevation Model

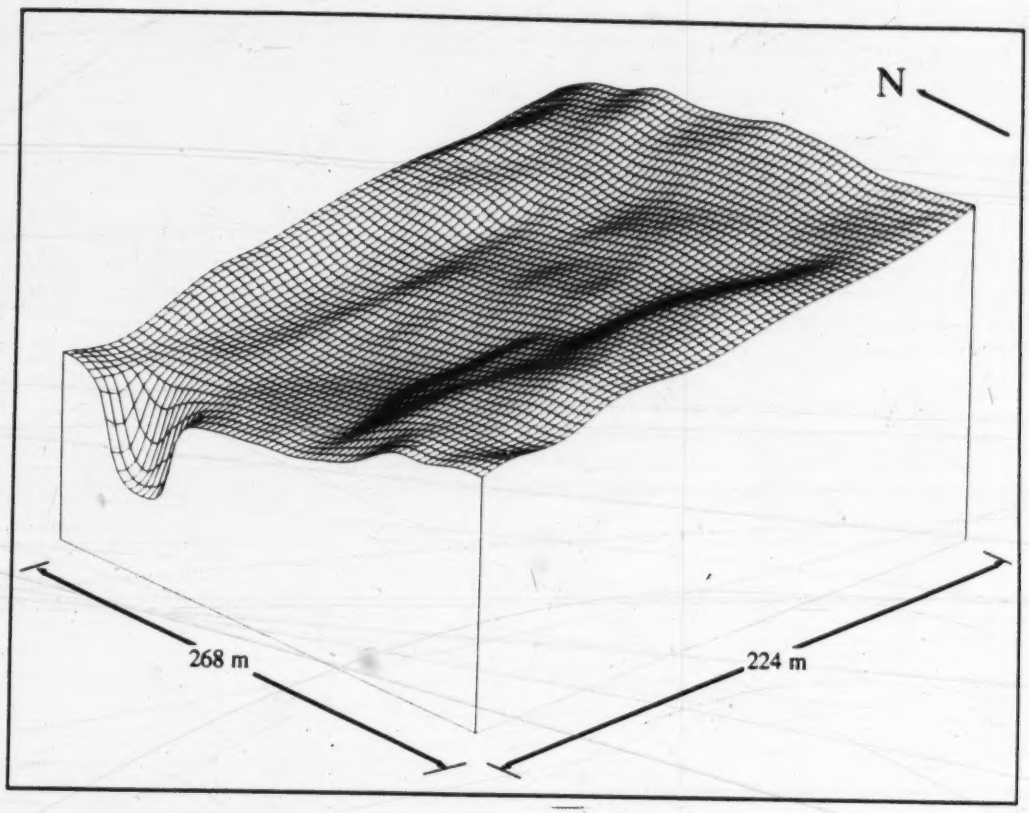

Figure 5.2 Graphical representation of the YS research basin (grid elements 4 x 4 m; some distortion due to plotting).

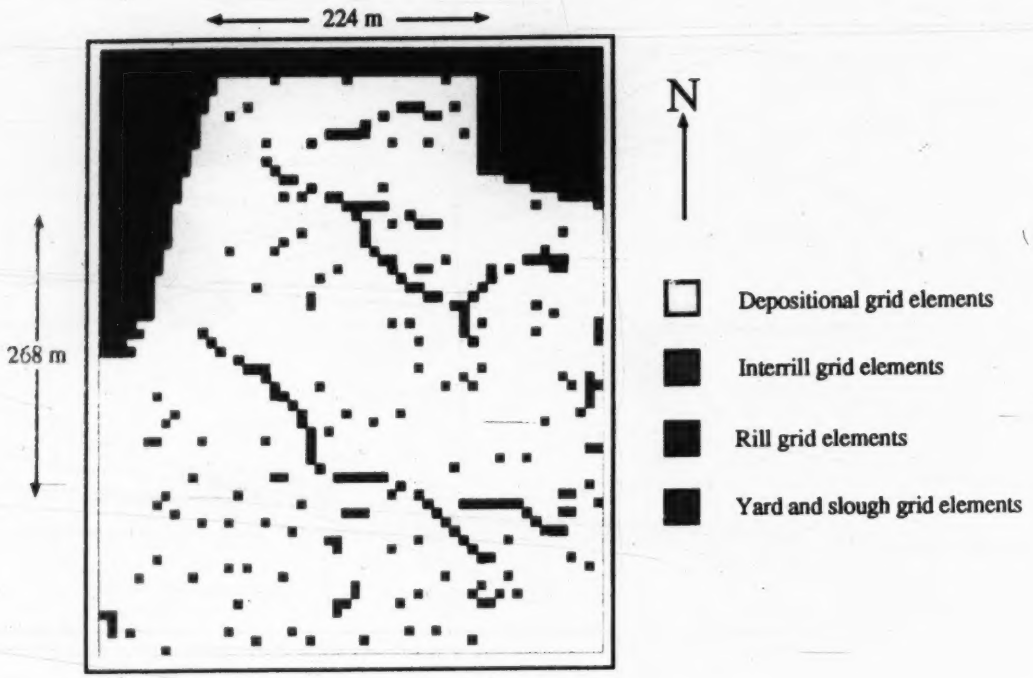

Figure 5.3 Locations of grid elements used in discriminant analysis.

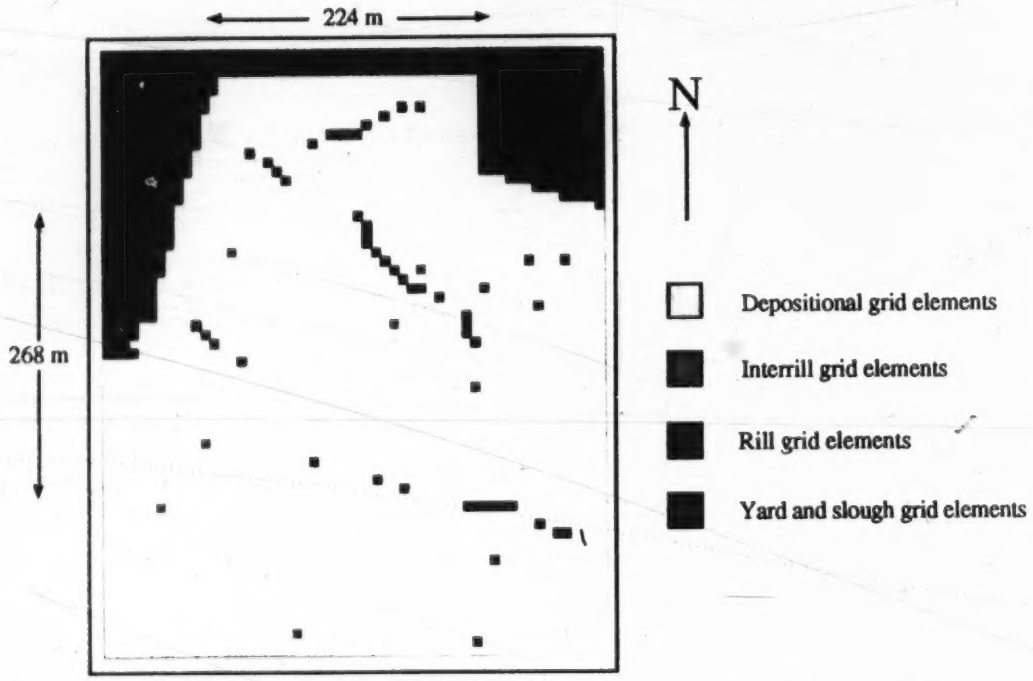

Figure 5.4 Locations of miss-classified rill grid elements from discriminant analysis.

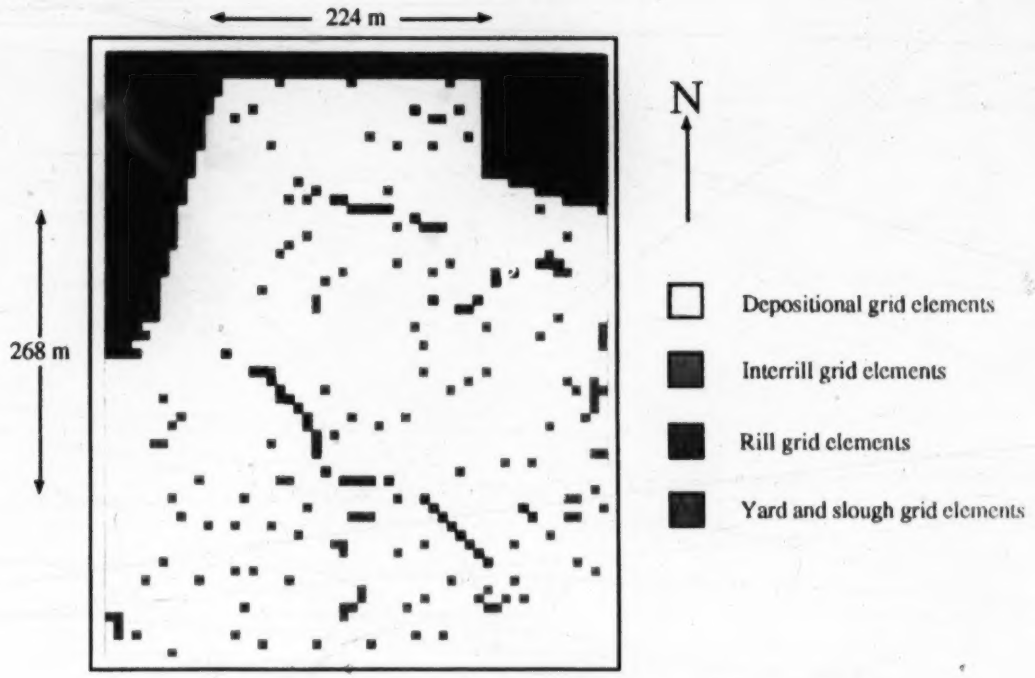

Figure 5.5 Locations of correctly classified rill grid elements from discriminant analysis.

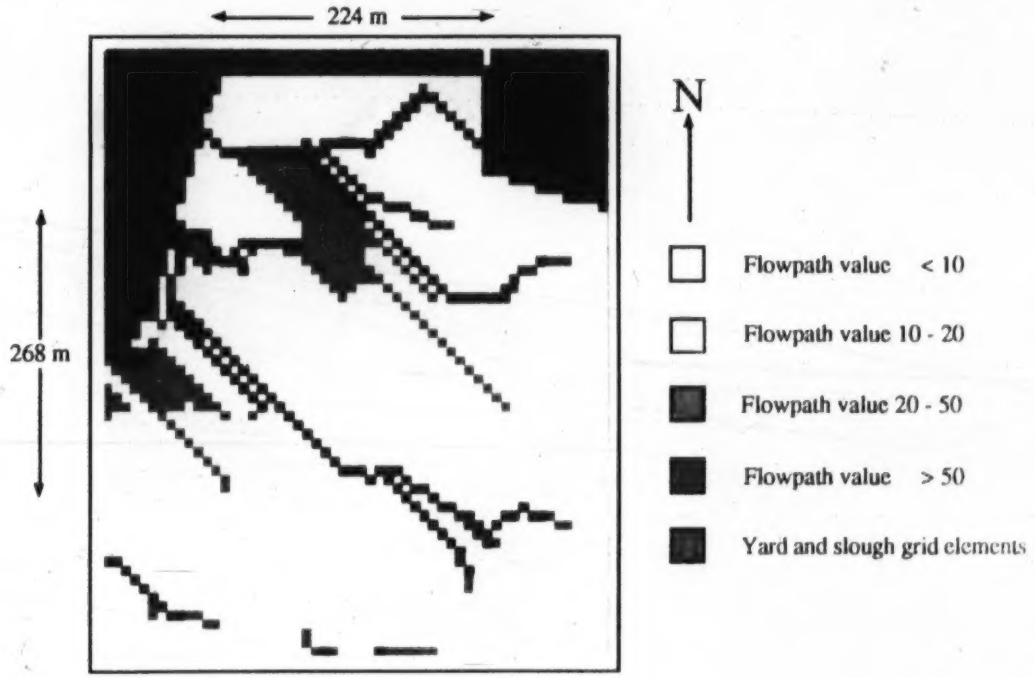

Figure 5.6 Flowpath map for YS basin.

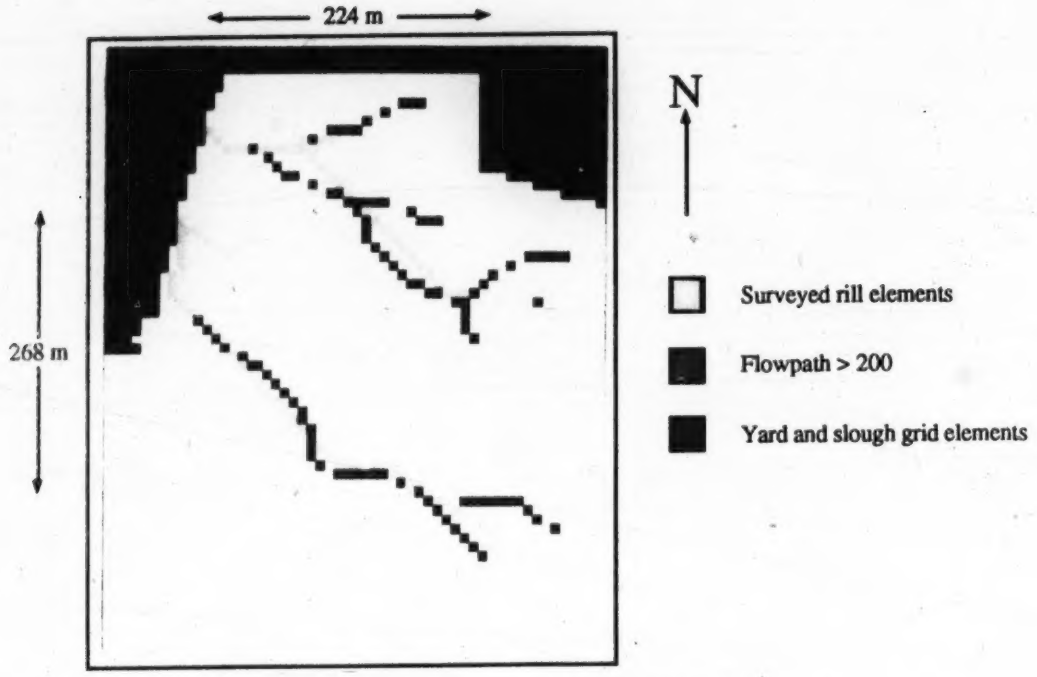

Figure 5.7 Surveyed rill network in relation to high (> 200) flowpath values.

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CHAPTER 6

SOIL PROPERTIES IN RELATION TO SURFACE FORM ON AN AGRICULTURAL FIELD IN EAST-CENTRAL ALBERTA

INTRODUCTION

Landscape analysis uses soil properties and landscape features to infer the location of physical processes. Mermut et al. (1983) used a landscape analysis technique, comparing cultivated to non-cultivated A horizon thicknesses, to measure soil erosion in southwestern Saskatchewan. Relationships were developed between slope gradient and A horizon thickness for both cultivated and non-cultivated landscapes. Erosion estimates were based on the difference in A horizon thickness for comparable slope positions and gradients.

Lanyon (1977) related soil properties to measures of surface form (gradient, curvature and aspect) to measure soil forming processes in an eastern Ohio drainage basin. Slope gradient, aspect and curvature were calculated from an elevation matrix. Land surface morphology was related to physical conditions such as soil moisture redistribution, energy balance and slope stability using digital terrain derivatives. Surface gradient was closely related to soil morphological and physical properties, particularly on south-facing slopes. Lanyon tested the hypothesis that topography is one of the soil forming factors that must be considered in the study of spatial patterns of soils in the landscape. Slope aspect, gradient and curvature are understood to have an impact on water runoff, incoming solar radiation and moisture balance and hence quantitative relationships between surface form and soil formation must exist.

Martz and de Jong (1985) used measures of land surface form (based on Evans 1972) to measure the relationship of soil erosion and deposition to land surface form. Erosion was estimated using ^{137}Cs and surface form was characterized using slope gradient and curvature (profile and contour) and measures of catchment and dispersal area. They found

that small percentages of the sites sampled had high amounts of soil deposition. Soil erosion occurred throughout the basin with some slope classes subject to higher amounts than others.

Pennock and de Jong (1987) also measured soil losses and gains on hummocky topography using ^{137}Cs. The majority of sites lost soil with a minority (11 to 17%) having soil gains. Net soil losses reported for three sites ranged from 9.5 to 16.9 t ha^{-1} yr^{-1}. Soil loss and soil gain values were compared with soil properties (A horizon thickness and depth to C horizon) by landform element classification. It is not entirely clear from the paper how the correlation analysis was conducted (values for all sites and all samples as compared to average values for each site or average values for all sites) but the authors concluded that soil morphology could not be used reliably to predict erosion or deposition. Other potential variables such as % organic carbon or mass of organic carbon were not considered in the correlation analysis.

Modeling erosion on a landscape basis requires data for soil properties and soil redistribution for every grid element. Unfortunately, any model of erosion on a landscape basis would involve many grid elements and therefore it would not be feasible to sample all of the grid elements of a model. If relationships between erosion, soil properties and digital terrain derivatives could be derived, then terrain derivatives, which are available for each grid element, could be used to estimate soil properties for grid elements that are not sampled. This paper examines evidence for relationships between soil properties that reflect erosion and land surface form for the purpose of identifying soil properties for unsampled grid elements and examining soil erosion processes.

MATERIALS AND METHODS

Soil profile characteristics thought to reflect erosion or deposition were used in conjunction with digital terrain derivatives to develop relationships between the two (Fig. 6.1).

Soil samples and soil profile descriptions were taken along six transects (Fig. 6.2) across the YS basin. The pattern of sampling followed a general north-south trend in the basin with some sampling between transect lines. The transects varied in length from 198 to 238 m and the number of sample points ranged from 11 on the shortest transect to 16 on the longest transect. The average distance between observations ranged from 18 m on the shortest transect to 15 m on the longest transect. Observations and samples were taken in locations characterized by interrill and rill erosion and deposition. Spacing of the observation points along each transect was variable because sampling point selection was based on observation of past erosional and depositional processes taken during the 1986 springmelt event. Observations and samples were taken between transects to characterize distinct erosional features or landform properties that were not found on the transect.

At each observation point the Ap/Ah horizon was sampled, horizon thickness was measured and depth to lime determined. Each of the observation points was classified as erosional, depositional or intermediate based on Ap/Ah horizon thickness and the presence or absence of B horizon mixed into the lower Ap/Ah horizon as follows:

If Ap/Ah > 20 cm then class = depositional,
If 15 cm < Ap/Ah < 20 cm then class = intermediate,
If Ap < 15 cm* and AB (mixed Ap and Bm) > 1 cm then class = erosional.
* based on local cultivation depth of 15 cm

The location of each of the 88 observations was mapped in the basin using a Zeiss total survey station. Each observation was then located in the same coordinate system as the DEM (Chapter 4) using the survey data to extract slope properties and flowpath values for the grid element sampled. Soil samples collected at each location were analyzed using standard techniques (McKeague 1978). Particle size distribution was determined by the pipette method; pH using the saturated paste method with water; exchangeable Na, Ca, Mg, K, and total exchange capacity using ammonium acetate extraction; organic carbon by Leco furnace; nitrogen by the Kjeldahl method. The mass of carbon was calculated by

multiplying the percent organic carbon value by an average bulk density (1.20 Mg m^{-3}) and horizon thickness.

The SAS procedure Proc Univariate was used to develop descriptive statistics, to test for normality and to develop frequency distributions for the three classes of grid elements (erosional, depositional and intermediate). Stem and leaf analysis, box plots and histograms were also produced for each of the three classes of grid elements using Proc Univariate prior to further statistical analyses.

Soil properties were related to slope properties and flowpath values for each grid element sampled using linear correlation (the SAS procedure Proc CORR). Analysis of variance was performed with Proc Anova to compare the means of slope gradient, downslope and across-slope curvature and flowpath for the three classifications of grid elements (erosional, depositional and intermediate). The means for the three classifications were compared using Duncans Multiple Range Test to determine which classifications were different or the same for specific individual digital terrain derivatives and soil properties.

Discriminant analysis of the three classes of grid elements (erosional, depositional and intermediate) was performed with Proc Discrim. Discriminant analysis is a statistical technique which is used to develop classification functions for classified data based on numeric variables. In this case, the numeric variables are the digital terrain derivatives and the classes are erosional, depositional and intermediate. All observations are used to develop the classification function. The function is then used to reclassify each of the observations in the data set and provide a measure of prior probability of membership to a particular classification. This analysis provides a tool to compare groups of classified data with one another, develop a function for classification and to classify other records with the same numeric variables into groups of classified data.

Discriminant analysis also provides a listing of all of the records used in the analysis, a classification based on the disciminant classifier, the original classification and the probability of membership in each classification. These data and Proc Univariate were

used to develop descriptive statistics, for the properly classified and the miss-classified grid elements (erosional, depositional and intermediate) in order to compare and contrast these three groups of data.

All of the erosional, depositional and intermediate grid elements were plotted in the basin using custom software developed by the author and standard plotting facilities of the Alberta Research Council. Properly classified and miss-classified grid elements (as per Discriminant analysis) were plotted in the basin to compare and contrast their locations in relation to the locations of originally classified grid elements.

RESULTS AND DISCUSSION

Of the 88 sampled grid elements, 37 (42%) were classified as depositional, 34 (39%) as erosional and 17 (19%) as intermediate or uncertain with respect to being erosional or depositional based on soil profile characteristics. The 88 sampled grid elements represent approximately 3% of the total number of grid elements in the basin.

Relationships Between Surface Form and Surface Horizon Properties

Soil properties were not strongly correlated with surface form. The highest correlation coefficients were for A horizon thickness in relation to: elevation (-0.30), gradient (-0.33), flowpath (0.49), across-slope curvature (-0.48) and downslope curvature (-0.35). The negative values of the correlation coefficients indicate that thinner Ap horizons are found on slopes with stronger gradients or on slopes with more positive curvature. Ap horizons ranging from 9 to 13 cm in thickness were found on moderately convex slopes (0.077 °/m across-slope and 0.092 °/m downslope curvature), Ap horizons from 9 to 20 cm in thickness were found on slightly convex slopes (0.069 °/m across-slope and 0.142 °/m downslope curvature) and Ap horizons greater than 20 cm in thickness were found on level to moderately concave slopes (-0.185 °/m across-slope and -0.120 °/m

downslope curvature). Thus, a weak relationship existed between slope gradient or curvature, and A horizon thickness.

Characteristics of Sampled Erosional, Depositional and Intermediate Grid Elements

Means and differences ($P \leq 0.05$) among means were calculated for those variables thought to reflect soil or land surface properties relevant in estimating soil erosion or deposition (Table 6.1). In general, the grid elements classified as depositional were significantly different from intermediate and erosional grid elements for Ah thickness (38.7 compared to 15.7 and 13.2 cm respectively), mean flowpath (70.1 compared to 8.5 and 6.7 counts respectively), downslope curvature (-0.120 °/m compared to 0.142 °/m and 0.092 °/m respectively) and across-slope curvature(-0.185 °/m compared to 0.069 °/m and 0.077 °/m respectively), slope gradient (3.5 ° compared to 4.7 ° and 4.6 ° respectively) and mass of carbon (12.0 kg/m^2 compared to 4.3 kg/m^2 and 3.6 kg/m^2 respectively). Grid elements classified as depositional were located in concavities in the landscape, had lower gradients than erosional or intermediate grid elements and had greater amounts of organic carbon. Depositional grid elements are clearly located in concave landscape locations that collect erosional sediment in the form of organic matter and that have higher flowpath values than erosional or intermediate grid elements. Classifying depositional grid elements in the basin thus seems feasible using digital terrain derivatives.

There were no statistically significant differences between the three classifications (erosional, depositional and intermediate) of grid elements for total exchange capacity, exchangeable Na, K, Mg or Ca (data not presented).

Depositional grid elements were statistically different from erosional grid elements in sand content (58.6% compared to 54.7% respectively) and clay content (14.1% compared to 16.9% respectively) whereas silt content was not statistically different for all three classifications. There was no statistical difference between intermediate grid elements and erosional or depositional grid elements for any particle size fraction. The greater sand

content and reduced clay content for depositional grid elements compared to erosional grid elements is due to the preferential detachment and transport of sand compared to clay.

The depositional grid elements were lower in the landscape (106.7 m) than erosional grid elements (108.1 m) but were similar to intermediate grid elements. The difference in absolute elevation between the mean depositional and erosional grid elements is 1.4 m and the difference in absolute elevation between depositional and intermediate grid elements is 0.4 m. The relationship is, however, not statistically significant. Depositional grid elements in the upper portion of the basin were in swales (concave across-slope and with positive downslope gradient) whereas depositional grid elements in the lower portion of the basin were characterized by concave curvature in both directions and low gradients.

The sampled erosional and intermediate grid elements were not statistically different for any of the variables measured. This indicates that surface form characteristics, soil physical and chemical properties, were similar for both classifications. Thus, the likelihood of differentiating these grid elements (erosional and intermediate) in the process of modeling water erosion would be expected to be low.

Discriminant Analysis of Sampled Erosional, Depositional and Intermediate Grid Elements

Although analysis of variance indicated that of the three classifications, the digital terrain derivatives for erosional and depositional grid elements were statistically different for some of the variables, there is no indication of which combination of variables makes each group unique. Furthermore, there is no way to classify other grid elements as erosional, depositional or intermediate based on the results of analysis of variance.

Discriminant analysis was used to develop a discriminant classifier for the sampled grid elements (Table 6.2). Of the 34 depositional grid elements sampled, 74% were correctly reclassified as depositional and 26% were miss-classified as erosional, whereas 78% of the erosional grid elements were correctly reclassified and 22% were miss-classified as depositional. Only 12% of the intermediate grid elements were reclassified

correctly with 76% miss-classified as erosional and 12% miss-classified as depositional. The erosional and depositional grid elements had distinctive surface form that could be used to identify these grid elements in simulation modeling. The intermediate grid elements did not have distinctive surface form given the low probability of reclassification. Most intermediate grid elements were reclassified as erosional, suggesting that surface form characteristics of intermediate grid elements were very similar to the erosional grid elements. The lack of differentiation of intermediate grid elements by discriminant analysis is congruent with the lack of statistical differentiation in analysis of variance of these grid elements.

The miss-classified erosional grid elements had the same mean gradient values (4.6 °) as did properly classified grid elements (Table 6.3). Miss-classified erosional grid elements had negative mean values for downslope (-0.18 °/m) and across-slope (-0.16 °/m) curvature whereas properly classified erosional grid elements had positive curvature values (0.17 and 0.14 °/m downslope and across-slope respectively). Miss-classified depositional grid elements had positive downslope and across-slope curvature values (0.03 and 0.13 °/m respectively) whereas properly classified depositional grid elements were characterized by negative curvature in both directions (-0.18 and -0.30 °/m downslope and across-slope respectively). Most strikingly, the miss-classified depositional grid elements had very low flowpath values (10) compared to the properly classified depositional grid elements (91). Miss-classified intermediate grid elements tended to have similar mean values for all slope properties to the properly classified erosional grid elements. Gradient and flowpath values for intermediate grid elements were close to values for erosional grid elements. Downslope and across-slope curvature values (0.08 and 0.07 °/m respectively) for miss-classified intermediate grid elements were positive but smaller in magnitude compared to properly classified erosional grid elements (0.61 and 0.60 °/m respectively).

The locations of miss-classified grid elements (Fig. 6.3) and correctly classified grid elements (Fig 6.4) did not reveal patterns in the basin as did the classified and miss-

classified rill, depositional and interrill grid elements (Chapter 5). The transects used in sampling the basin were evident in the location of classified and miss-classified grid elements. The second most westerly transect in the basin is obvious from the number of miss-classified grid elements (Fig. 6.3) but there is no explanation why this transect would be characterized by a larger number of miss-classified grid elements compared to other transects. The transect sampling pattern in the basin is obvious from the pattern of properly classified grid elements.

CONCLUSIONS

The results of analysis of sampled grid elements indicates that those elements classified in the field as being erosional or depositional have distinctive surface form characteristics that could be used in classifying unsampled grid elements into these categories. The grid elements classified in the field as being intermediate between erosional and depositional grid elements tended to be closer to erosional grid elements in terms of surface form. These grid elements should be treated as erosional grid elements in simulation modeling since they lack distinctive surface form characteristics and are similar to erosional grid elements. This finding is congruent with the conclusion (Chapter 5) that only very small portions of the YS basin are subject to high amounts of erosion and deposition and that much larger portions of the basin are subject to very low amounts of erosion.

The approach of relating soil properties to surface form measurements worked well in the YS basin where a detailed elevation data set was available and where detailed soil sampling had taken place. The relationship between surface form and erosion category developed from discriminant analysis is not considered valid for any other setting or with other elevation data sets, particularly those with different vertical and horizontal resolution. Detailed elevation data sets are relatively easy to obtain for small research sites but to obtain the detail necessary to model soil properties on a larger scale would be very difficult.

Table 6.1 Means for variables thought to reflect erosion or deposition for each of the three classes of erosion, deposition and intermediate grid elements.

Variable	Mean for Grid Elements Classified as Erosional N=37	Mean for Grid Elements Classified as Intermediate N=17	Mean for Grid Elements Classified as Depositional N=34
Elevation (m)	108.1a*	107.1a	106.7a
Flowpath (counts**)	6.7b	8.5b	70.1a
Downslope curvature (°/m)	0.092a	0.142a	-0.120b***
Across-slope curvature (°/m)	0.077a	0.069a	-0.185b
Slope Gradient (°)	4.6a	4.7a	3.5b
Ap/Ah Mass of Carbon (kg/m^2)	3.6a	4.3a	12.0b
Ap/Ah Sand content (%)	54.7b	56.9ab	58.6a
Ap/Ah Silt content (%)	28.4a	27.6a	27.3a
Ap/Ah Clay content (%)	16.9a	15.4ab	14.1b

N = number of samples.
* means in a given row with same letter are not significantly different at $P \leq 0.05$.
** flowpath values are counts per grid element.
*** negative sign denotes concave curvature.

Table 6.2 Percent of grid elements re-classified by discriminant analysis into the three identified groups.

Original Classification	Percent of nodes classified into:			
	Deposition	Erosional	Intermediate	N
Deposition	74	26	0	34
Erosional	22	78	0	37
Intermediate	12	76	12	17

N = number of samples.

Table 6.3 Means for properly classified and miss-classified grid elements from discriminant analysis.

Location	Landscape property	Units of measure	N (miss-classified)	Mean (miss-classified)	N (properly classified)	Mean (properly classified)
Erosional	gradient	°	8	4.6	29	4.6
Deposition			9	4.6	25	3.4
Intermediate			15	4.6	2	6.3
Erosional	downslope curvature	°/m	8	-0.18	29	0.17
Deposition			9	0.04	25	-0.18
Intermediate			15	0.08	2	0.61
Erosional	across-slope curvature	°/m	8	-0.16	29	0.14
Deposition			9	0.13	25	-0.30
Intermediate			15	0.07	2	0.61
Erosional	flowpath	counts*	8	7	29	7
Deposition			9	10	25	91
Intermediate			15	9	2	6

N = number of samples.
* the flowpath calculation is in counts per grid element.

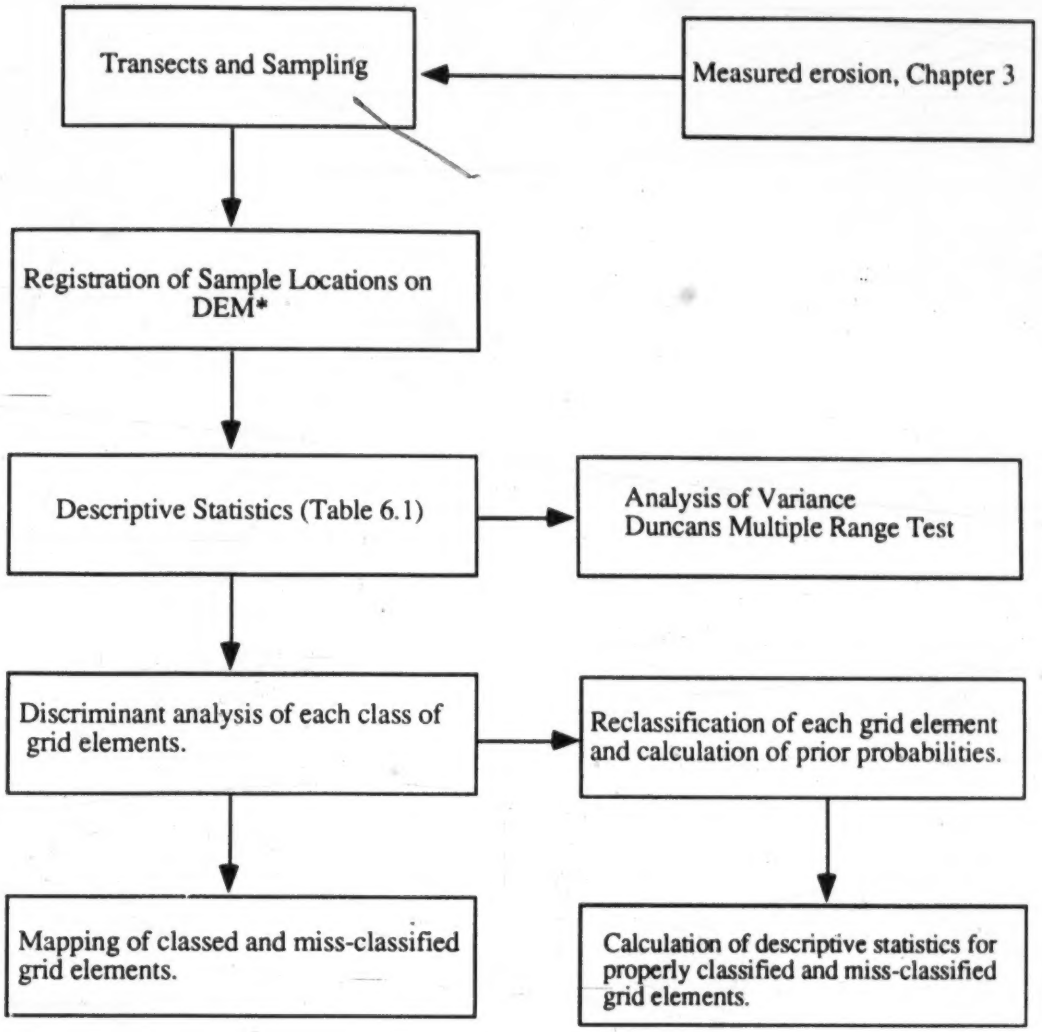
Transects and Sampling
Measured erosion, Chapter 3
Registration of Sample Locations on DEM*
Descriptive Statistics (Table 6.1)
Analysis of Variance
Duncans Multiple Range Test
Discriminant analysis of each class of grid elements.
Reclassification of each grid element and calculation of prior probabilities.
Mapping of classed and miss-classified grid elements.
Calculation of descriptive statistics for properly classified and miss-classified grid elements.

Figure 6.1 Flow chart of research methods and analyses (Chapter 6).

* Digital Elevation Model

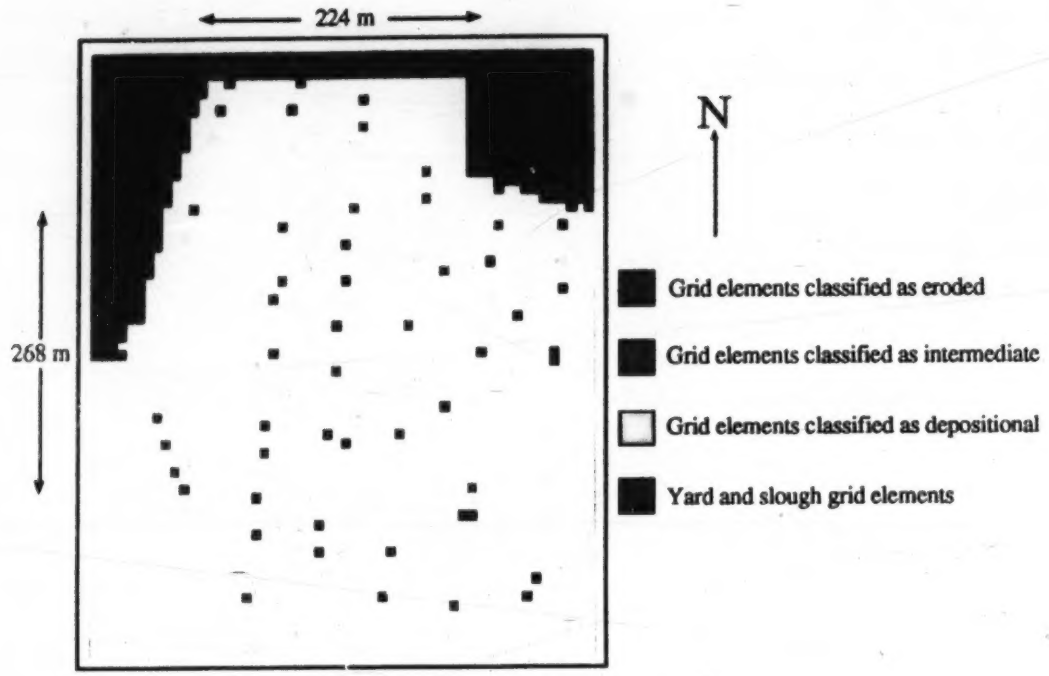

Figure 6.2 Locations of sampled grid elements in the YS basin.

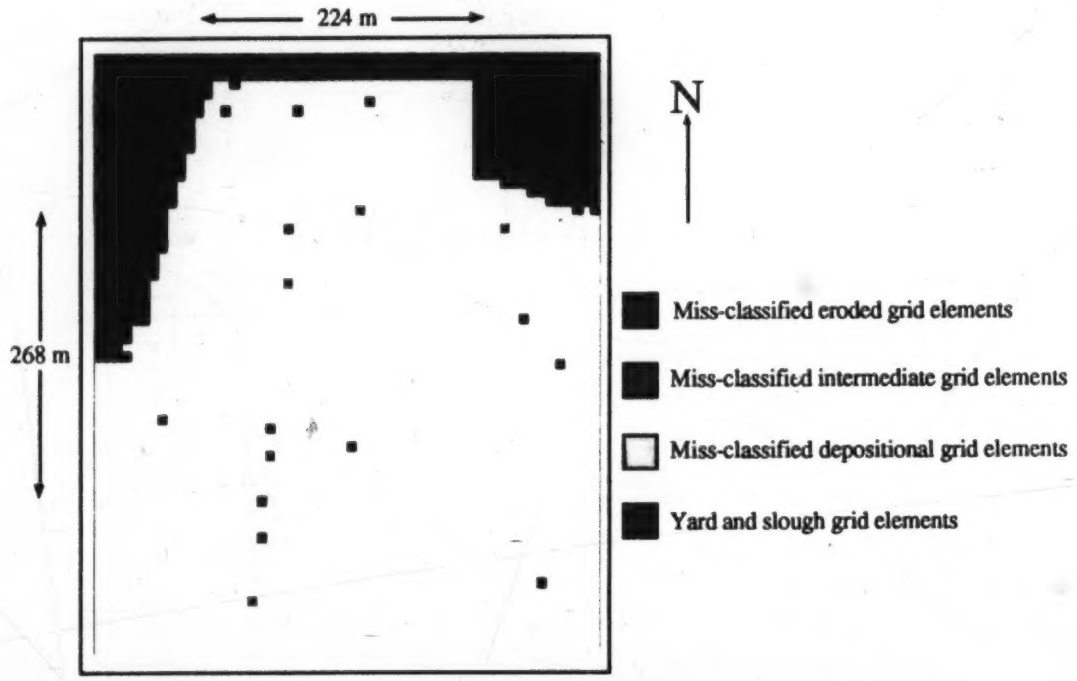

Figure 6.3 Locations of grid elements miss-classified by discriminant analysis.

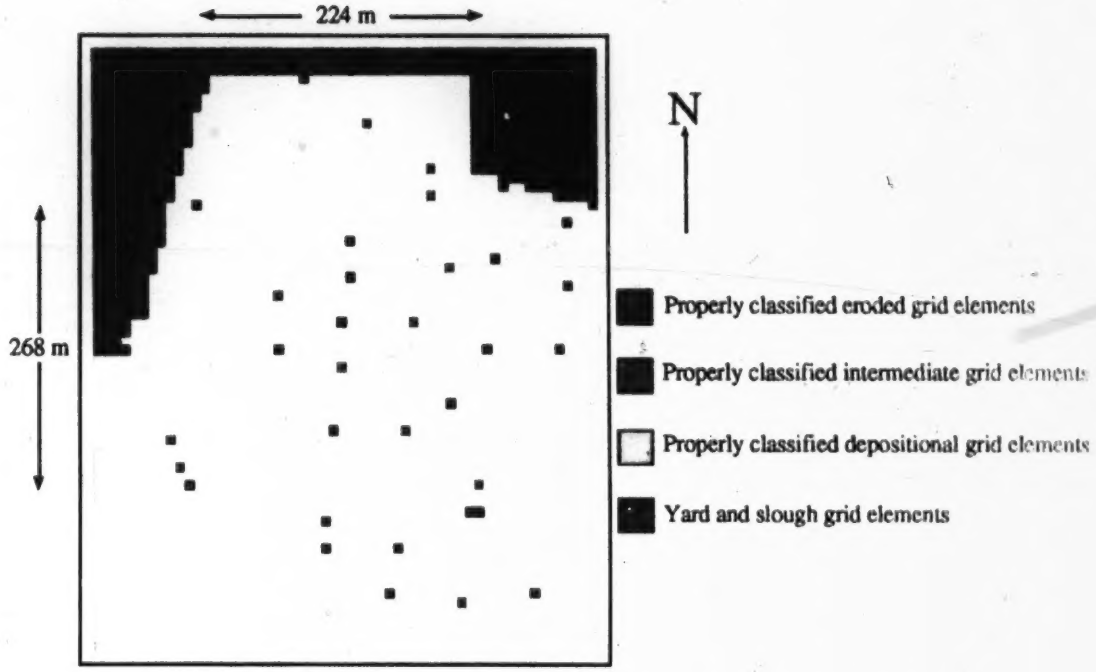

Figure 6.4 Locations of grid elements properly classified by discriminant analysis.

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CHAPTER 7

A CONCEPTUAL APPROACH TO MODELING SOIL EROSION

INTRODUCTION

Several techniques were used to measure soil erosion on different landscape elements at several sites in east-central Alberta. Rill erosion was found to be the dominant type of erosion accounting for soil redistribution on the landscape. Rill erosion affected only very small portions of the landscape whereas the largest portion of the landscape was dominated by interrill erosion which accounted for substantially less soil loss. Soil deposition also occurred on very small portions of the landscape. Most of the soil eroded by rill and interrill processes was deposited within the basin of origin as compared to being lost to the surface water system (rivers and streams).

Modeling soil erosion provides an opportunity to study the cumulative effects of continued erosion over time on soil and landscape properties and to examine the effects of different management schemes and changing climate on the amount and distribution of erosion processes. The purpose of this chapter is to discuss the significance of the research and to present a conceptual approach to modeling soil erosion and deposition on an agricultural landscape. The conceptual model considers the spatial and temporal variability of erosion. The structure, implementation and limitations of the conceptual model are also discussed.

SIGNIFICANCE OF RESEARCH

At the outset of this research project soil erosion was reported to be a continuing and persistent problem in east-cental Alberta based on field observations during soil survey activities (Wyatt et al. 1944; Macyk et al. 1985; Howitt 1988). During the course of this research erosion from springmelt and summer rainfall was measured in each of the three

field seasons. The frequency of erosive meteorological events for the sites under study was 1 to 2 events per year. Therefore, the probability of erosion occurring at a site in any given year is low. With the continued use of summerfallow in east-central Alberta, the probability of continued erosion across the region would be higher than at any individual site.

In most years the magnitude of measured erosion at the study sites in east-central Alberta was low because of the sporadic nature of erosive meteorological events and changing land use. Soil loss values ranged from a few milligrams in the case of interrill erosion to 83.9 Mg for rill erosion during summer rainfall. Summer rainfall resulted in 3.8 times as much rill erosion as occurred during springmelt. The value of the topsoil lost from upper slopes by rill erosion to depressional locations in the field is difficult to determine either in terms of lost productivity or increased input costs (tillage, fertilizer). Therefore, the significance of continued erosion losses of the magnitude measured in this study is also difficult to determine.

The impacts of soil gains are also difficult to determine. One result of continued rill erosion in YS basin was the filling of a depression with eroded topsoil resulting in improved accessibility to the area by cultivation equipment. Improved productivity in areas of deposited topsoil has been discussed by some but there are no data to support or negate this assertion. Negative impacts of continued rill erosion could result from the deposition of subsoil material over topsoil and subsequent reductions in productivity and soil quality for plant growth.

Field studies of soil erosion and deposition on agricultural landscapes were critical to measuring the characteristics of erosion. The open landscape approach provided a mechanism to study erosion in response to naturally occurring erosive events, in relation to land surface form. Complex surface form, as described by gradient, curvature in two directions and flowpath values, was an important component in measuring and modeling soil erosion. Single measures of 'erosion' e.g., plot studies, ^{137}Cs, erosion pans, rill

meter, rainfall simulation, etc. do not capture the full spectrum of erosion processes on their own but when they are used in conjunction with one another (e.g., pans and rill meter), a more detailed view of the system is revealed.

Soil redistribution on agricultural landscapes includes soil loss and soil gain depending on landscape position and surface form characteristics whereas soil erosion includes only soil detachment and transport. Concave slope elements with positive downslope curvature and gradient that are adjacent to similar slope elements were subject to rill erosion. Concave slope elements with negative downslope and across-slope curvature and low gradient were subject to soil deposition. Convex landscape elements and landscape elements with limited curvature and gradient were subject to small amounts of interrill erosion as indicated by pan measurements.

Time is an important variable in field measurement of erosion. The occurrence of springmelt and convective rain storms is so variable in time that measuring the effects of these events is very difficult and requires long term study. It is unlikely that the full range of erosion intensities possible in east-central Alberta was experienced in the study period.

The spatial variability of the factors controlling erosion processes is another reason why field studies of erosion are important but difficult to accomplish. The variability of convective rain storms across the landscape and the distribution of snow cover during springmelt are tedious and expensive to measure and model. Soil loss and soil gain are highly variable on the landscape. The majority of measured erosion and deposition occurred on very small percentages of the landscape. Less than 5% of the landscape in the study area was subject to either rill erosion or deposition and the majority of the landscape was subject to very low rates of interrill erosion.

Estimates of erosion based on uniform soil loss over some area and which also neglect soil gain do not adequately reflect the nature of soil redistribution. The majority of measured soil loss occurred as a result of rill erosion and the measured soil loss resulted in soil deposition on the landscape. The concept of soil loss must be balanced with soil gain

and must be considered in terms of landscape position. The concept of average annual soil loss must be mediated by an understanding of the spatial and temporal variability of erosion processes.

The theoretical models of erosion, discussed in Chapter 1, do not take into consideration complex surface form and the relationships between landscape elements. Most, if not all, of the theoretical models discussed treat the land surface as a flat plane over which water and soil move.

This research provided a basis for quantitative measurement of the characteristics of soil erosion on a natural basin under conventional farming management. Erosion, deposition and soil properties were measured in the field and linked to surface form characteristics (gradient, curvature and flowpath) through discriminant analysis.

The proposed conceptual model provides a framework for modeling soil erosion and deposition processes on agricultural landscapes. Occurrence of sporadic erosive events and land management can be modeled using probability techniques. Response of landscape elements to erosive events can be determined using digital terrain modeling techniques and simulation modeling.

CONCEPTUAL APPROACH TO EROSION MODELING

Three concepts are fundamental to understanding and modeling soil erosion on a landscape basis. These concepts are:

1. Soil redistribution is the dominant process resulting from erosive meteorological events on agricultural landscapes in Western Canada, e.g., erosion is accompanied by deposition in some portion of the landscape,
2. Soil redistribution is controlled in large measure by erosive meteorological events that can be modeled explicitly. The intensity,

duration and impact of erosive meteorological events are highly variable in space and time, and

3. The occurrence and amount of soil redistribution is highly variable across the landscape for any given erosive event. Different portions of the landscape are eroding at different rates as controlled by surface form, surface condition, soil properties and the magnitude and nature of the erosive event (snowmelt, variable rates of precipitation, etc.).

The question at hand is whether there is a modeling approach which is not so empirical as to ignore the processes involved in soil erosion but which does not involve detailed soil erosion mechanics where data requirements can become onerous and solutions difficult to validate. An attempt was made to to find a middle ground with respect to the approach taken to modeling soil erosion processes (physically based and empirical), which also accounts for the spatial and temporal variability of soil erosion on agricultural landscapes. These concepts, along with the conclusions reached in Chapters 3 through 6, have been used to develop a model of soil erosion.

MODELING TECHNIQUES RELEVANT TO SOIL EROSION

Soil erosion modeling provides a framework to test theories about natural processes and estimate the response of systems to changing conditions and inputs. Simulation modeling involves the use of mathematical representations of a system to estimate or predict the response of a system. There are several approaches to modeling natural systems to emulate (not duplicate) processes.

Most natural systems are too complex to be evaluated analytically to obtain exact information on questions of interest and therefore, simulation modeling is used to estimate the desired characteristics of the process in question (Law and Kelton 1982). Simulation modeling provides a framework for asking the 'what if' question without the need to spend years of intensive research work to find out a probable answer to the question. For

example, the USLE was developed after many years of plot experimentation. The resources required to develop the USLE were substantial and in retrospect there are some inherent difficulties in using the model. Efforts in erosion modeling should be aimed at 'what if' questions that reduce the need for intensive field research and help target field testing to validate specific issues or problems.

There are many ways to define and classify simulation modeling techniques. Law and Kelton (1982) distinguished six types of mathematical or simulation models: static, dynamic, deterministic, stochastic, discrete and continuous. Static models were described as being a representation of a system at a point in time (e.g. a Monte Carlo simulation), whereas dynamic simulation models are representations of systems as they evolve over time (i.e. changing surface form in relation to continued soil loss and deposition). Deterministic models contain no random variables and there is a unique set of model outputs for a given set of inputs. Stochastic models, on the other hand, contain one or more random variables and therefore the output from a stochastic model are random and different for every situation. Discrete simulation models are event driven in that changes to the representation of the system can only occur at finite points in time whereas with continuous models, state variables can change continuously with respect to time. Law and Kelton (1982) discussed each of these and a variety of related topics including simulation languages, probability and statistics, probability distribution functions, random number generation and validation of simulation models. The selection of one or a combination of modeling techniques must reflect the nature of the system being studied.

Saaty and Alexander (1981) discussed a range of modeling techniques with the purpose of 'formulating' as compared to 'solving'. They suggested a need for structuring and formulating problems creatively and that formulation is a 'mystery relegated to the not yet well understood process of creativity'. By way of example, solving, they report, 'is an established art in our colleges, universities and scientific laboratories'. Use of the USLE is quite straightforward for most soil scientists. Formulating and structuring the problem of

how soil erosion occurs (rill, interrill, deposition, climate, management, soil properties and soil redistribution) are less simple.

A PROPOSED MODEL FOR SOIL EROSION ON AGRICULTURAL LANDSCAPES

The conceptual model (Fig 7.1) consists of five components, each of which is a stand-alone model, connected to other components by calling routines or functions. The calling routines serve to exchange data and information between the components. The conceptual model provides a framework within which a simulation model could be developed for the YS basin given time, resources and additional data.

In order for a model to be efficient and physically correct, processes that have the greatest influence on the overall model must be given priority over less influential processes. The proposed model takes into account complex surface form as quantified using digital terrain modeling techniques for modeling soil redistribution. Agricultural landscapes can have marked differences in slope gradient and curvature (across and downslope) and individual slope elements respond in relation to adjacent slope elements. Therefore, they cannot be treated as plane surfaces as is the case with many models, WEPP in particular, but also the formulation of Rose (1985). The proposed model reduces the uncertainty associated with extrapolation of plot data to agricultural landscapes. The soil redistribution component of the model and the use of discriminant analysis to classify the landscape into rill, interrill and depositional elements consider the landscape variability in soil redistribution processes.

The approach of using digital terrain derivatives and soil properties components is similar in nature to the work of Khanbilvardi and colleagues and more recently Bork and Rohdenburg (1986). This approach incorporates the ability to deal with the spatial variability of soil erosion, soil properties and conditions affecting soil erosion. The

temporal aspects of these processes can also be addressed using multiple runs with different initial and boundary conditions.

A second purpose of the model is to take into account, explicitly, the probability of an erosive climatic event occurring at a time when the soil surface is bare and susceptible to soil erosion. The climatic probabilities and cropping management components of the model are designed to simulate the temporal variability in soil erosion events.

Climatic Probabilities Component

This component is central to the model because the occurrence of erosive meteorological events is a primary controlling factor in the occurrence of soil erosion on the land surface. The measured erosion discussed in Chapter 4 occurred as a result of short duration events which occurred sporadically over the period of study. This component of the model would focus on accounting for the spatial and temporal occurrence of erosive meteorological events. The output of this component would trigger the soil redistribution component in conjunction with the cropping management component to initiate soil redistribution.

The climatic probabilities component consists of a discrete-event simulation of an erosive event. For each time step, a probability distribution function(s) is sampled to determine the probability of an event for that time step. Functions to describe convective summer storms and springmelt are needed. This component can be designed to simulate rainfall, rainfall on frozen ground and springmelt events as discussed by Brown et al. (1985) and Istok and Boersma (1986). Frequency distribution functions, similar to those developed in the Pacific Northwestern United States, can be developed for conditions in Western Canadian and then used in simulation of erosive events. This component would be a discrete or event-driven simulation using random number generation to sample the frequency distribution function for erosive events.

Cropping and Management Component

The cropping and management component of the model keeps track of the condition of the soil surface (bare soil compared to emerging crop cover or established crop cover) with time in relation to cropping and land management systems. The variety of management practices used by farmers in Western Canada can be simulated using discrete simulation techniques by setting variables as true of false, based on the current state of the cultivation pattern. A variety of management practices are used by farmers in Western Canada. These practices are well documented in terms of crop rotations. Data collected to date could be used to estimate surface conditions from year to year. For example, summerfallow conditions can occur periodically throughout a simulation. This component also facilitates the simulation of soil conditions during the course of the year by taking into account the fact that even during years that crops are produced, the soil is often highly erodible in the early spring into June due to seedbed preparation. The timing of operations (tillage, seeding, harvesting), crop emergence and growth for specific rotations and crops are documented and could be incorporated into the model. Other factors such as runoff over a frozen soil surface in spring can also be included in simulation. The output of this component would be used in conjunction with the output of the climatic probabilities component to trigger the soil redistribution component to initiate simulation of soil redistribution.

Soil Redistribution Component

The soil redistribution component is the engine in this model that accounts for the movement of soil from areas of erosion to areas of deposition. The amount of soil erosion for each grid element in the model must be estimated based on the intensity and nature of the erosive event, on the state of the cropping and management component and the shape of the land surface based on the digital terrain component. It was originally anticipated that the amount of erosion for each grid element in the model could be established based on

field measurements of ^{137}Cs and that an elementary continuous simulation would best describe the redistribution of soil on the landscape. The measurement of the occurrence and distribution of soil erosion on the landscape indicated that discrete simulation is better suited to the redistribution component of the model. Erosion events generated by the climatic probabilities component would trigger the assignment of amounts of soil loss for all rill and interrill grid elements on an event basis. The amount of erosion assigned to each grid element would depend on the classification of each grid element as determined with a discriminant classifier in the digital terrain component. The amount of soil loss for each grid element could be established by sampling a probability distribution function of soil loss values for rill and interrill erosion based on the data presented in Chapter 4 or average values could be calculated for each type of grid element. A routing scheme would be used to redistribute eroded material to areas of deposition.

The effects of rill erosion will have to be distributed over a larger area than the rill grid elements because in effect, tillage operations fill and smooth rill patterns by dragging soil from adjacent areas in the field. This can be accomplished by identifying a buffer area adjacent to each of the rill grid elements from which soil can be removed and added to the rill grid elements. This would necessitate a return to the soil properties and digital terrain components of the model to adjust A horizon thickness and elevation. In similar fashion, the soil redistribution component must distribute eroded material over the area of deposition. Changes in horizon thickness and elevation for all grid elements form the output from the soil redistribution component which is then used in the soil properties component to keep track of these changes and provide output.

Digital Terrain Component

The digital terrain component consists of a quantitative description of the land surface form. The digital terrain component of the model consists of an array of elevation data from which equivalent arrays of slope gradient, across and downslope curvature and

flowpath are generated. This component would contain the algorithms for calculating digital terrain derivatives and flowpath values. The derivative arrays are used by a discriminant classifier to identify rill, interrill and depositional grid elements in the model for use in the soil redistribution component. An algorithm for connecting rill grid elements into a network of rill grid elements would have to be developed. During the course of a simulation, changes in the elevation of rill and depositional grid elements would probably change sufficiently to necessitate a return mechanism to the digital elevation component for recalculation.

Soil Properties Component

The soil properties component is an accounting package designed to establish and then keep track of the changes in soil properties during simulation. Discriminant analysis would be used to identify erosional and depositional grid elements and then assign soil properties values to every grid element based on the results of Chapter 6. The classification of erosional or depositional would not be used in the soil redistribution component in favour of using the rill, interrill and depositional classifications for modeling. The soil properties component would receive data on changes to soil properties during the course of simulation, store the changes and the current values. This data would be used during and at the end of simulation to provide output on soil properties, changes in soil properties and summary statistics.

Discussion Of Time Step Used In Simulation

The time step used in any simulation is critical to both the computing resources required for simulation and the results obtained. Bare soil will be exposed and susceptible to erosion every year due to seed bed preparation or to summerfallow. The time step of simulation must be such that this factor can be taken into account and also recognize that in winter and once a crop is established there is a very low probability of soil erosion. A variable time step would be required for this model to operate with optimum computational

efficiency and in order to take into account the temporal variability of both climatic probabilities and cropping practice. A daily time step would be necessary to model erosion on summerfallow throughout the growing season and during the period prior to crop emergence. A monthly time step would be appropriate during the period of springmelt (February to April) because springmelt occurs over a period of several days and would likely only occur once in any given month.

Model Output

The model would keep track of and print changes to the soil properties component during and at the end of simulation along with summary statistics on simulated erosion losses and gains by grid element type (rill, interrill and depositional). Graphical representation of changes to surface form and soil properties would also be very beneficial in evaluating the results of simulation.

Implementation Of The Conceptual Model

The model would be best implemented using Fortran or C as compared to using existing simulation languages such as CSMP, GPSS or SLAMM, primarily because the latter require many computing resources and therefore are quite expensive to use.

Object-oriented programming would be entirely appropriate in the implementation of a simulation model. For example, rill patterns and depositional areas could be modeled as objects which would respond in very a specific manner to erosion events. Slope segments within the basin could also be modeled as entities as opposed to grid element by grid element basis. There would be significant computational advantages to using object oriented-programming techniques.

Limitations Of The Conceptual Model

The model is limited in applicability to small agricultural watersheds with reasonably detailed datasets for elevation, soil properties and measurements of actual versus predicted

erosion. The issue of spatial scale transference (de Boer and Campbell 1989) must be considered when considering this model in any other setting or at any other scale such as would be the case in watershed modeling. de Boer and Campbell found that the behavior of the mesoscale basin was dominated by behavior of mesoscale elements rather than by the microscale elements it contained.

The mesoscale rill processes, which are the dominant soil redistribution processes in the YS basin, would probably not be evident at a scale very much greater than the scale of this study. The slope characteristics used in this study to classify rill grid elements would not apply to a study with 100 m grid elements. The issue of thresholds across which spatial scale transference cannot take place without extensive revision should form an important part of spatial scale research in geomorphology (de Boer and Campbell 1989). The research contained herein strongly suggests that soil erosion studies on agricultural landscapes must also take into consideration spatial scale transference. Extrapolation from traditional plot scale studies (microscale) to fields or to basins is not straightforward because of complex topography and because individual elements of the landscape are affected by other landscape elements. For example, one grid element in the model may have the surface form characteristics of an interrill grid element but because there is some number of rill grid elements upslope from this grid element, it may behave as a rill grid element during erosion events.

The model is designed for farm scale modeling of soil redistribution and requires considerable inputs in the form of elevation and soil properties data. Thus, model validation for the YS basin and for other similar basins in east-central Alberta would be a very large undertaking and many years of research would be required to cover the range of possible erosion events.

The climatic probabilities component of the model would be difficult to implement because the weather records for the prairie provinces are not adequate to develop probability distribution functions for intense summer rainfall. Radar records are available

for central Alberta from the Penhold radar facility and might provide a data source for this component of the model. The probability distribution function for springmelt could be developed from existing meteorological records by recording consecutive days of above freezing temperatures during spring.

Digital terrain modeling techniques provide a tool to describe, quantitatively, parts of the landscape but do not as yet provide the relationships between adjacent and connecting landscape elements which is needed to fully model erosion processes. Scale of erosion process and scale of digital terrain modelling must be addressed explicitly in an erosion modeling perspective. Rills are generally a meter or two wide, 10 to 15 cm in depth and 10 to several 100 m in length. The DEM used in this study had a grid spacing of 4 m and vertical resolution of 10 cm and with it rill grid elements were identified and classified using discriminant analysis. With better resolution in the DEM, the percentage of properly classified rill grid element might have been higher, but only to a point. With poorer resolution the percentage of properly classified rill grid elements would have been lower, to a point where the DEM would be at an appropriate scale to differentiate rill erosion.

The relationships between surface form, erosion process and erosion category developed with discriminant analysis are not considered valid for any other setting or with other elevation data sets, particularly one with different vertical and horizontal resolution. Detailed elevation data sets are relatively easy to obtain for small research sites, but it would be very difficult to obtain the detail necessary to model soil properties on a larger scale.

FUTURE RESEARCH

The research described herein was focussed on the development of the input data and manipulation for the first three components: the digital terrain, soil properties and soil redistribution components. The climatic probabilities and the cropping management components of the model described herein are the least developed of the components and require the greatest amount of future work. Data on the spatial and temporal occurrence of

convective summer storms on the prairies are limited. Statistics on the timing and intensity of springmelt events are not readily available. This component requires research because the occurrence of erosive meteorological events is a primary controlling factor in the occurrence of soil erosion.

The question of' how much resolution in a DEM is necessary to model soil properties?' has not been addressed in this research. The resolution of a DEM must have sufficient horizontal and vertical resolution to identify surface form characteristics of rill and depositional grid elements and research is necessary to determine optimum resolution. Research into the relationships among grid elements and how those relationships impact on erosion estimates for individual grid elements is necessary. For example, the flow of water through a rill grid element is affected by adjacent grid elements as well as grid elements that are further upslope in the rill network. The development of a way to characterize these relationships would be helpful to efforts in erosion modeling.

The impacts of continued erosion, of the magnitude documented herein, on lost productivity, increased input costs and reduced soil quality should be investigated on a landscape basis. The balance of possible yield increases in areas of deposition compared to yield reductions in eroded areas should be included in this research.

Studying soil erosion at fixed sites is problematic given the sporadic nature of erosive meteorological events (spatial and temporal). Future research on the extent of erosion should focus on erosion events as compared to erosion at selected sites.

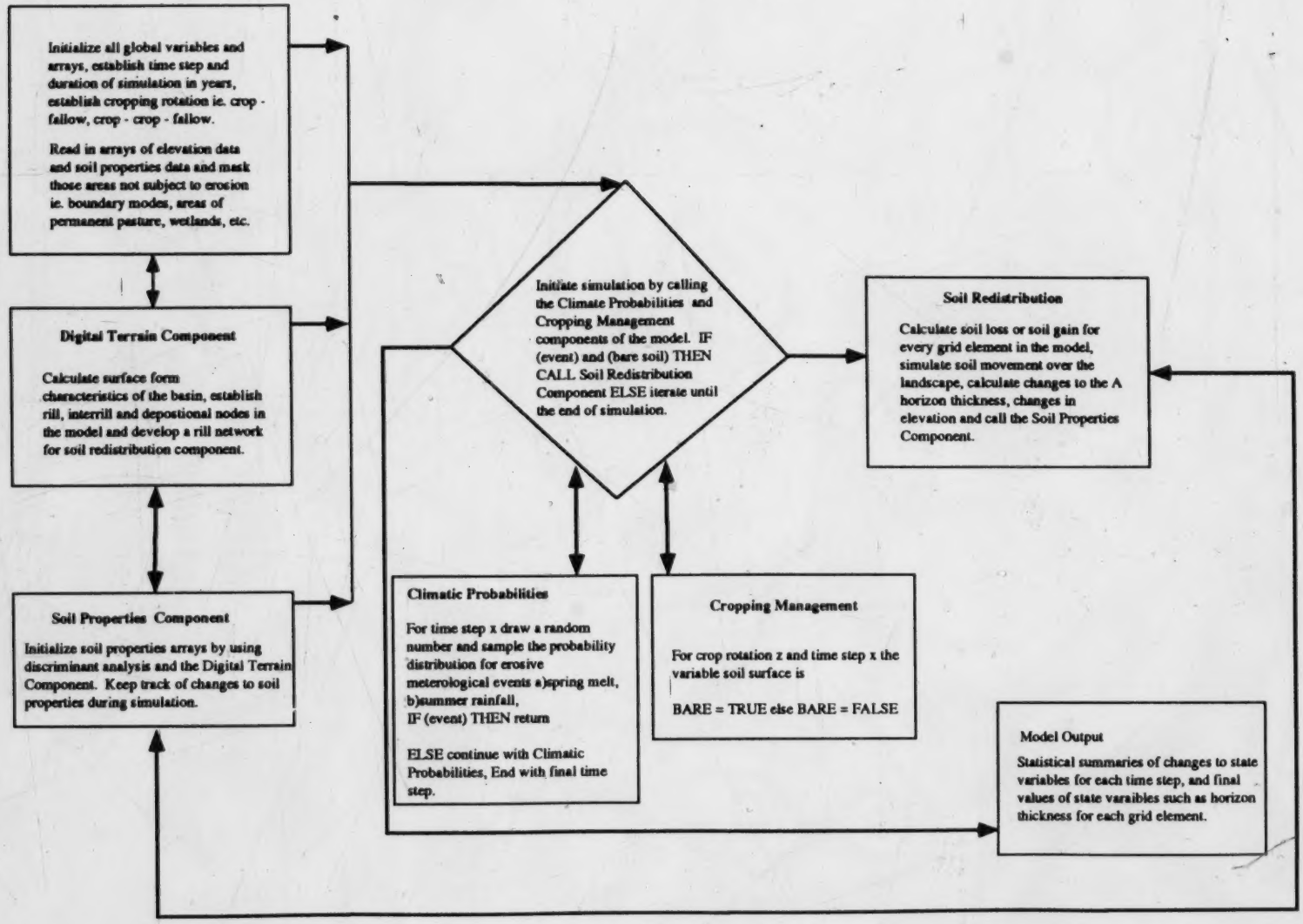
Initialize all global variables and arrays, establish time step and duration of simulation in years, establish cropping rotation ie. crop - fallow, crop - crop - fallow.
Read in arrays of elevation data and soil properties data and mask those areas not subject to erosion ie. boundary modes, areas of permanent pasture, wetlands, etc.
Digital Terrain Component
Calculate surface form characteristics of the basin, establish rill, interrill and depostional nodes in the model and develop a rill network for soil redistribution component.
Soil Properties Component
Initialize soil properties arrays by using discriminant analysis and the Digital Terrain Component. Keep track of changes to soil properties during simulation.
Initiate simulation by calling the Climate Probabilities and Cropping Management components of the model. IF (event) and (bare soil) THEN CALL Soil Redistribution Component ELSE iterate until the end of simulation.
Soil Redistribution
Calculate soil loss or soil gain for every grid element in the model, simulate soil movement over the landscape, calculate changes to the A horizon thickness, changes in elevation and call the Soil Properties Component.
Climatic Probabilities
For time step x draw a random number and sample the probability distribution for erosive meterological events a)spring melt, b)summer rainfall,
IF (event) THEN return
ELSE continue with Climatic Probabilities, End with final time step.
Cropping Management
For crop rotation z and time step x the variable soil surface is
BARE = TRUE else BARE = FALSE
Model Output
Statistical summaries of changes to state variables for each time step, and final values of state varaibles such as horizon thickness for each grid element.

Figure 7.1 Flow diagram of conceptual erosion model.

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